
**Pacific Northwest
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Final Technical Report: Development of the DUSTRAN GIS-Based Complex Terrain Model for Atmospheric Dust Dispersion

(SI-1195)

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May 2007

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14. ABSTRACT The verified and documented dust dispersion modeling system (DUST TRANsport or DUSTRAN) was developed to address particulate air quality issues at military training ranges from fugitive dust sources. This development effort was funded by the Strategic Environmental Research and Development Program (SERDP) with partial funding from the US Environmental Protection Agency (EPA) and the Forest Service to extend DUSTRAN to address their issues related to the "off-target" drift of aerially applied pesticides. DUSTRAN is based on widely-used atmospheric models and model components. The modeling system efficiently couples these modeling components and advances the state-of-science in dust-emission formulations based on SERDP-funded field studies (Projects SI-1191 and SI-1399) for determining dust emission factors from vehicle activities. DUSTRAN is based on a commercially available geographic information system (GIS) and EPA-approved atmospheric dispersion models. DUSTRAN also includes formulations for estimating particulate concentrations from wind-generated dust emissions.					
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Acronyms and Abbreviations

CALGRID	CALifornia photochemical GRID model
CALMET	CALifornia METeorological model
CALPOST	CALifornia POST-processing program
CALPUFF	CALifornia PUFF model
DEM	digital elevation model
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRI	Desert Research Institute
DUSTOP	DUSTRAN Operational Program
DUSTRAN	DUST TRANsport
EPA	U.S. Environmental Protection Agency
ESRI	Environmental System Research Institute
ESTCP	Environmental Security Technology Certification Program
FORSCOM	U.S. Army Forces Command
FS	U.S. Forest Service
GIS	geographic information system
GLCC	global land cover characteristics
GUI	graphical user interface
LST	local sidereal time
M-O	Monin-Obukhov (similarity theory)
NOAA	National Oceanic & Atmospheric Administration
NWS	National Weather Service
NTC	National Training Center
OFCM	Office of the Federal Coordinator for Meteorology
PGT	Pasquill-Gifford-Turner specifications
PM	particulate matter
PNNL	Pacific Northwest National Laboratory
PST	Pacific Standard Time
SERDP	Strategic Environmental Research and Development Program
SPRAYTRAN	Spray TRANsport modeling system
TEOM	tapered element oscillating microbalance
UTM	Universal Transverse Mercator

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Ms. Crystal Driver and Mr. Randy Kirkham of PNNL provided field data from studies conducted at the National Training Center, Fort Irwin, California, for initial testing of the modeling system. These studies were conducted by PNNL through funding from the U.S. Army Forces Command. Dr. Jack Gillies of Desert Research Institute (DRI) provided emission-factor data for wheeled military vehicles. The emission factors were developed under SERDP project SI(formerly CP)-1191 “Characterizing and Quantifying Local and Regional Particulate Matter Emissions from Department of Defense Installations” with DRI.

Dr. Robert Holst, the past SERDP program manager, provided invaluable guidance and support during all phases of the development of DUSTRAN, and Dr. John Hall, the current SERDP program manager, helped guide the final efforts for completing DUSTRAN. Additionally, Dr. Harold Thistle of the U.S. Forest Service and Ms. Sandy Bird of the U.S. Environmental Protection Agency provided important guidance and insight in adapting DUSTRAN to treat the off-target drift of pesticides. Dr. Jim Droppo of PNNL provided valuable reviews and guidance during completion and final testing of the modeling system.

Executive Summary

Activities at U.S. Department of Defense (DoD) training and testing ranges can be sources of dust in local and regional airsheds governed by air-quality regulations. Activities that generate dust by disturbing local surfaces include vehicle and troop maneuvers, convoy movement, helicopter activities, munitions impacts, roadway preparations, and wind erosion. The use of smokes and obscurants, controlled burns, and engine operations also produce particulates.

The U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) just completed a multi-year project to develop a fully tested and documented atmospheric dispersion modeling system (DUST TRANsport or DUSTRAN) to assist the DoD in addressing particulate air-quality issues at military training and testing ranges. DoD's Strategic Environmental Research and Development Program was the primary source of funding for the project with additional funding from the U.S. Forest Service and U.S. Environmental Protection Agency (EPA) to address their issues related to the "off-target" drift of aerially applied pesticides.

DUSTRAN is constructed from widely used, scientifically defensible atmospheric models and model components. The modeling system efficiently couples these modeling components and advances the state-of-science in dust-emission formulations. DUSTRAN is based on Environmental System Research Institute's ArcMap geographic information system (Version 9.x), the EPA-approved CALifornia PUFF (CALPUFF) dispersion model, and the widely used CALifornia GRID (CALGRID) dispersion model. The CALifornia METeorological (CALMET) model provides the meteorological fields (e.g., winds, mixing height) for the CALPUFF and CALGRID dispersion models. The modeling system runs on a personal computer under the Microsoft Windows XP operating system. DUSTRAN includes dust-emission models for estimating emissions from both wheeled military vehicle activities and dust generated by wind erosion. The primary features of DUSTRAN are:

- The modeling domain is graphically specified and is size selectable (20 km to 400 km).
- It operates at any U.S. geographic location and has an "Add Site" wizard that generates a new site's supporting files and data structure for use in a simulation.
- Single-station or multiple-station meteorology can be used and easily specified.
- Multiple point, area, and line releases can be accommodated and specified graphically.
- Simulation and release times are easily specified in the user interface.
- The output concentrations and deposition contours can be viewed graphically, and the output can be animated to view the progression of the plume across the modeling domain.
- Multiple particle sizes and gaseous species can be simulated at one time.
- Simulation periods are typically a few hours to a few days.
- The atmospheric models treat wet and dry deposition and complex terrain effects.

The wheeled-vehicle PM₁₀ (particulate matter less than 10 microns aerodynamic diameter) emission factors from the Strategic Environmental Research and Development Program (SERDP) project SI(formerly CP)-1191 "Characterizing and Quantifying Local and Regional Particulate Matter Emissions from Department of Defense Installations," (see

<http://www.serdp.org/research/CP/CP-1191.pdf>) and the dust emission factors from EPA's AP-42 document for wheeled vehicles operating on paved and unpaved roads form the basis of the current vehicle-generated dust-emission model in DUSTRAN. Current SERDP projects SI-1399 "Particulate Matter Emissions Factors for Dust from Unique Military Activities" and SI-1400 "Development of Emission Factors for Dust Generated by Unique Military Activities" (see http://www.serdp.org/research/CP/CP_1399.pdf and http://www.serdp.org/research/CP/CP_1400.pdf) will provide dust-emission factors over the next few years from field studies investigating unique military dust-generating sources, such as tracked vehicles, fixed-wing and rotary-wing aircraft, and artillery back-blast. These new emission factors will be incorporated into DUSTRAN within the SI-1399 project as they become available.

The wind-generated dust-emission model in DUSTRAN is based on formulations from the current scientific literature. These formulations relate wind characteristics, soil texture categories, and vegetation cover categories to dust flux (mass per unit area per unit time) into the atmosphere. DUSTRAN includes files of soil-texture categories and vegetation-cover categories covering the contiguous United States for estimating dust emissions from wind erosion. If finer resolution files of soil texture and vegetation cover are available for a specific area, DUSTRAN allows these finer resolution files to be used.

Since the CALPUFF atmospheric dispersion model in DUSTRAN is an EPA "recommended" model, the dispersion (transport and diffusion) components of the model have already been validated against tracer data. Limited field data are available for validating DUSTRAN for proper simulation of dust emissions from military-vehicle activities on unpaved roads and in off-road training areas. DUSTRAN computations compared favorably with PM₁₀ concentrations measured at several locations during a day of move-out operations at Fort Irwin, California. DUSTRAN also compared favorably with windblown dust measurements for dust generated at the DOE Site at Hanford, Washington. The results of the wind-generated dust simulations are currently being prepared for submission to a scientific journal.

The first step in transitioning DUSTRAN for operational use at military training ranges has been completed by making the DUSTRAN modeling system's User's Guide and installation CDs available from PNNL. DUSTRAN has also recently been applied at a military training range. At the request of the Fort Bliss, Texas, air programs manager, DUSTRAN was successfully used to estimate the impacts of Fort Bliss move-out and combat training activities on PM₁₀ air quality in the vicinity of Fort Bliss. Two reports giving the DUSTRAN results for Fort Bliss were provided to the air-programs manager, and DUSTRAN is currently being installed at Fort Bliss for use by the air-programs manager.

A reasonable approach for effectively transitioning DUSTRAN for broad application at military ranges is through a multi-year transition project (possibly through the Environmental Security Technology Certification Program) implementing the use of DUSTRAN at two-to-three military installations at various locations in the United States. The project will allow appropriate military staff to be trained in the use of DUSTRAN and will permit application of DUSTRAN to installation-specific air-quality issues. Implementation at multiple military installations will facilitate the DUSTRAN user interface being made more "friendly" by ongoing interaction

between the users and DUSTRAN developers. It also will identify clearly those features of DUSTRAN that are most important to military users, thus allowing proper prioritization of potential DUSTRAN extensions and enhancements. A multi-year transition project will facilitate finding an organization willing and capable of long-term support of the DUSTRAN system for providing technical consulting, software maintenance, and periodic upgrades as operating systems change and technical advances are made.

1.0 Objective

The primary objective of this research was to develop a fully tested and documented atmospheric dust dispersion modeling system (DUSTRAN or DUST TRANsport) for use in complex terrain to help manage dust-generating activities at military ranges, to estimate range contributions to local and regional air quality, and to help develop dust mitigation strategies. This research responded to the U.S. Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) Statement of Need (CPSON-01-03) for characterizing dust emissions from range activities. A principal element of this research was to implement dust-emission factors for wheeled-vehicle movement in the DUSTRAN modeling system (Gillies et al. 2005b) developed by the Desert Research Institute (DRI). These emission factors were developed within the SERDP project “Characterizing and Quantifying Local and Regional Particulate Matter Emissions from Department of Defense Installations,” research project SI(formerly CP)-1191.

To achieve this primary objective and to verify that the modeling system was not only easy to use but also produced results likely to be accepted by both regulators and atmospheric-science professionals, the project also had the following secondary objectives:

- To incorporate models sanctioned, approved, or otherwise recognized by the U.S. Environmental Protection Agency (EPA).
- To verify that incorporated models adequately allow for the effects of complex terrain (e.g., enhanced diffusion, flow blocking and channeling, slope flows) on dispersion.
- To provide estimates of dust generated by active processes, such as military or civilian vehicle activity on dirt roads and other unpaved areas, and by natural processes, such as wind erosion.
- To utilize a graphical information system (GIS) interface familiar to military and civilian personnel to facilitate simulation setup and to display simulation results.
- As much as possible, to automate and make transparent to the user the software engineering tasks of formatting input files, running modules in the proper sequence, and graphically displaying results from various output files.

2.0 Background

Activities at DoD training and testing ranges can be sources of dust in local and regional airsheds governed by air-quality regulations. Activities that generate dust by disturbing local surfaces include vehicle and troop maneuvers, convoy movement, helicopter activities, munitions impacts, roadway preparations, and wind erosion. Other sources of particulates include the use of smokes and obscurants, controlled burns, and engine operations.

Predicting or tracking the dispersion (transport and diffusion) of dust in complex terrain requires several important components, including 1) a fast atmospheric-dispersion model using meteorological data from a network of weather stations, 2) a dust-emission model quantifying the release from dust-generating activities, 3) a resuspension model from dust generated by wind erosion, and 4) a user-friendly GIS-based interface for specifying run conditions and graphically viewing dust transport throughout the region of interest. The foundation for developing a user-friendly atmospheric dust-dispersion modeling system is to assemble the best system from available, defensible, well-tested, and documented components rather than building the system from scratch. The current status of each of the modeling system components is summarized below:

- 1) Numerous atmospheric dispersion models (OFCM 1999) are available that include features for properly treating dispersion and deposition of particulates over a range of particle sizes. The CALifornia PUFF (CALPUFF) atmospheric dispersion model (Scire et al. 2000a) is an excellent candidate model for this research because it is an EPA-approved guideline model for addressing air-quality issues for transport distances from a few-hundred meters to a few-hundred kilometers. CALPUFF treats complex terrain effects and can treat numerous sources characterized as point, line, or area releases. A critical goal of the dust-dispersion modeling system developed in this research is that the atmospheric dispersion models are not modified such that they maintain their EPA “guideline model” status. Additionally, the original source code must be available to accommodate recompilation, if needed, for compatibility with current computer operating systems. The original Fortran source code for the CALPUFF models is available from Earth Tech, Inc. (<http://www.src.com/calpuff/calpuff1.htm>).
- 2) Currently, no dust-emission factors for military training and testing activities are available other than those developed by the completed SERDP project SI(formerly CP)-1191 “Characterizing and Quantifying Local and Regional Particulate Matter Emissions from DoD Installations” (Gillies et al. 2005b) for wheeled-vehicles on unpaved roads and the relatively new ongoing SERDP projects SI-1399 “Particulate Matter Emissions Factors for Dust from Unique Military Activities” (Gillies 2006) and SI-1400 “Development of Emission Factors for Dust Generated by Unique Military Activities” (Kim 2006) for tracked vehicle, aircraft, artillery, and other unique dust-generating military activities. The wheeled-vehicle PM₁₀ (particulate matter less than 10 microns aerodynamic diameter) emission factors from SERDP project SI-1191 and the dust-emission factors from EPA’s AP-42 document (EPA 2005) for wheeled vehicles operating on paved and unpaved roads will be used for the modeling system.

- 3) The current scientific literature (e.g., Gillette and Passi 1988; Nickovic et al. 2001) has formulations for estimating wind-generated dust emissions from the earth's surface. These formulations relate wind characteristics, soil-texture categories, and vegetation-cover categories to dust flux (mass per unit area per unit time) into the atmosphere.
- 4) The commercially available Environmental System Research Institutes' (ESRI's) ArcMap GIS (Version 9.x) is widely used nationally and internationally for numerous types of applications needing the flexibility of assembling and viewing various types of geographic information. The software architecture of ArcMap allows for developing specific extensions that can be coupled to ArcMap for seamless operation. That is, the extension can be operated as a part of ArcMap with the features of ArcMap available for use by the extension. Using ArcMap as the foundation of the graphical user interface (GUI) for the dust-dispersion modeling system allows a widely used programming language (Visual Basic) to be used to integrate ArcMap functionality with user-input windows and the graphical display of model results (e.g., particulate air concentrations). Additionally, using Visual Basic, the ArcMap programming language allows the execution of the Fortran-based atmospheric dispersion models to be controlled by the modeling system.

The final element in a successful modeling system is having proper field data for model validation. Since an objective of this research is to use EPA-approved atmospheric dispersion models, validation of the transport and diffusion (collectively, dispersion) components of the modeling system is not necessary. For example, the CALPUFF modeling system has been validated using data from tracer experiments (EPA 1998). By using CALPUFF in the DUSTRAN modeling system, it is not necessary to validate the dispersion components of DUSTRAN. The DUSTRAN components that must be validated are the PM₁₀ source-term models for both vehicle-generated and wind-generated dust. Limited data are currently available for validating these dust-emission components.

The field data needed to validate the vehicle-generated PM₁₀ source model of DUSTRAN are meteorological quantities (e.g., winds), PM₁₀ air concentrations, and location and timing of all vehicle activity during a military training exercise. The only field data set sufficient to validate the DUSTRAN vehicle-generated PM₁₀ source model is that collected during training exercises at the National Training Center (NTC) at Fort Irwin, California. The data were collected by the U.S. Department of Energy's (DOE's) Pacific Northwest National Laboratory (PNNL) for the U.S. Army Forces Command (FORSCOM). A sufficient number of PM₁₀ measurements were made surrounding the vehicle activity areas such that impacts of the training activities were distinguishable from ambient PM₁₀ concentrations. Additionally, sufficient details on the activities of all vehicles in the training exercises were available to specify the vehicle activities within DUSTRAN. Allwine et al. (2004) have provided a comparison of DUSTRAN simulations with the Fort Irwin field data.

Other field studies have been conducted at military training ranges investigating the impacts of military activities on particulate matter (PM) air quality. For example, Kirkham et al. (2005) recently conducted field studies at Fort Stewart, Georgia, measuring PM concentrations and meteorological quantities at various locations on Fort Stewart. Even though the Fort Stewart

field data set is fairly thorough for characterizing PM air quality on Fort Stewart, it is not sufficient to validate the DUSTRAN vehicle-generated dust-emission model because no major training exercise was characterized in sufficient detail during the air-quality characterization studies. Gillies et al. (2005a) measured PM₁₀ concentrations at four locations on Fort Bliss during the “Roving Sands” military exercise on June 13–25, 2001. This data set was appropriate for characterizing PM₁₀ concentrations on Fort Bliss, but is not sufficient for validating the DUSTRAN vehicle-generated dust-emission model. The PM₁₀ measurement locations are too few and sometimes too distant (depending on the wind direction) from the locations of the training activities for properly measuring the impacts of the training activities on PM₁₀ air quality.

Several years of PM₁₀ concentrations and meteorological data have been collected at several locations on DOE’s Hanford Site located in eastern Washington State. The soil texture and vegetation cover across the Hanford Site have been characterized for use in validating the wind-generated dust source model in DUSTRAN. This Hanford Site data set is being used to validate DUSTRAN for use in simulating PM air concentrations resulting from wind-generated dust. In addition, Gillies et al. (2005b) found that disturbance of the soil surface from military activities on “test plots” at Fort Bliss was observed to exacerbate wind erosion and dust emissions where the degree of increase was linked to how much loose sand was created by the activity. The wind-generated dust emissions from the Fort Bliss test plots were reduced by an order of magnitude after 3 years. The reduction of dust emissions was attributed to the development of soil crusts and the establishment of a significant cover of vegetation. These wind-erosion studies at Fort Bliss were conducted using a small portable wind tunnel.

3.0 Materials and Methods

As discussed in the previous section, the foundation for developing a user-friendly atmospheric dust dispersion modeling system is to assemble the best system from available, defensible, well-tested, and documented components rather than building the system from scratch. This is the method taken in developing the DUSTRAN modeling system—the result of this research project. The task structure, listed below, used to develop the DUSTRAN modeling system parallels the five primary system components described in the previous section. The foundations and design criteria for each task are also given in the previous section and will not be repeated in the following list of tasks.

- 1) Identify and Implement Dispersion Models—Candidate dispersion models were reviewed, and models were chosen that satisfy the DUSTRAN design criteria (e.g., CALPUFF and CALGRID, with meteorological model CALMET and associated pre- and post-processors). The model inputs and outputs were identified for coupling to the GIS-based user interface. Additionally, the interactions of the input and output files and dispersion model executable codes are controlled by the underlying software architecture.
- 2) Develop Vehicle-Generated Dust-Emission Model—Using wheeled vehicle-generated dust-emission factors from SERDP project SI-1191 and AP-42 emission factors for vehicles on paved and unpaved roads, a vehicle-generated dust-emission model was developed. This emission model provides emission files to the dispersion models based on vehicle activity locations and timing.
- 3) Develop Wind-Generated Dust-Emission Model—Using formulations from the scientific literature, a wind-generated dust-emission model was developed that produces dust flux as a function of location and time using temporally and spatially varying wind speed as well as spatially varying soil texture and vegetation cover. The dust-emission file produced from the wind-generated dust-emission model is used in the dispersion model to estimate PM concentrations from wind-generated dust.
- 4) Develop DUSTRAN User Interface Coupled to a GIS—The graphical user interface for specifying model inputs and viewing model outputs was developed using the programming language (Visual Basic) common to the ArcMap GIS. This approach allows for the user-input windows and the functionality of the GIS to seamlessly interact.
- 5) Validate DUSTRAN Using Field Data—As indicated in Section 2.0, the results of DUSTRAN wind-generated dust simulations and the Hanford Site data-set comparisons are currently being prepared for submission to a scientific journal. As also indicated in Section 2.0, limited field data exist for validating DUSTRAN for proper simulation of dust emissions from military vehicle activities on unpaved roads and in off-road training areas. Additionally, since the atmospheric dispersion models in DUSTRAN are EPA guideline models, the dispersion components of DUSTRAN have already been validated against tracer data.

An important element of a successful dust-dispersion modeling system is having thorough documentation and having the modeling system available on installation CDs or via the Internet. This has been accomplished by preparing the DUSTRAN user's guide (Allwine et al. 2006b) and its accompanying DUSTRAN installation disks. Internet downloads via the PNNL public ftp site are possible, and we are investigating making a limited version of DUSTRAN available directly on the Internet. Additionally, encouraging widespread use of the DUSTRAN modeling system through an effective transition plan is essential for maximizing the benefit of DUSTRAN in addressing PM air-quality issues at military facilities. An integral part of a successful modeling system is long-term funding for technical support as well as software maintenance and periodic upgrades as operating systems change and technical advances are made.

4.0 Results and Accomplishments

Beginning January 2001, this multi-year research project was started to develop an atmospheric dispersion modeling system to assist the DoD in addressing particulate air-quality issues at military training and testing ranges. The efforts at PNNL were funded primarily by SERDP. The U.S. Forest Service (FS) and the EPA have also provided funds towards developing the atmospheric modeling system. The FS and the EPA need to address issues related to the “off-target” drift of aerially applied pesticides. They consequently have funded a portion of the development program for the modeling-system user interface and funded wholly the development of a separate pesticide-source-term module. Allwine et al. (2006a) describe the Spray TRANsport (SPRAYTRAN) modeling system used to assess the off-target drift of aerially applied pesticides.

The culmination of this work has led to the development of the DUST TRANsport, or DUSTTRAN, modeling system. DUSTTRAN is a comprehensive dispersion modeling system, consisting of a dust-emission model, a diagnostic meteorological model, and dispersion models that are integrated seamlessly into ESRI’s ArcMap GIS. DUSTTRAN functions as a console application within ArcMap and allows the user to interactively create a release scenario and run the underlying models. Through the process of data layering, the model domain, sources, and results—including the calculated wind-vector field and plume contours—can be displayed with other spatial and geophysical data sources to aid in analyzing and interpreting the scenario.

This section gives an overview of the basic components of DUSTTRAN and provides a detailed description of its vehicle-generated and wind-generated dust-emission models. An example simulation using DUSTTRAN is given demonstrating the basic instructions for operating the software. Finally, a comparison of DUSTTRAN results with field data is given. Allwine et al. (2006b) provide detailed DUSTTRAN user instructions, and Allwine et al. (2004) provide more information on comparing DUSTTRAN results with field data.

4.1 DUSTTRAN Basic Components

The DUSTTRAN user interface integrates the input and output operations needed for evaluating potential air-quality impacts. The three primary components of DUSTTRAN and their linkages, illustrated in Figure 4.1, have the following functionalities:

- GIS for specifying geographical inputs (e.g., modeling domain, surface characteristics, activity locations) and for viewing model outputs (e.g., spatially and temporally varying dust concentration and deposition fields).
- Dust-emission model for determining dust-emission rates as a function of time and location for various dust-generating activities specified in a simulation.
- Dust-dispersion models for simulating dispersion and deposition to determine the ground-level air concentration and deposition patterns.

The GIS component is based on ESRI's ArcMap GIS (Version 9). DUSTRAN can be configured for application at any U.S. geographical location. New sites can be added using an "Add Site" wizard that creates the required files and data structures. The GIS user interface implemented in DUSTRAN includes the capability to graphically define simulations by:

- Creating a model domain and its surface characteristics
- Specifying modeling domain size by selecting dimensions ranging from 20 to 400 km

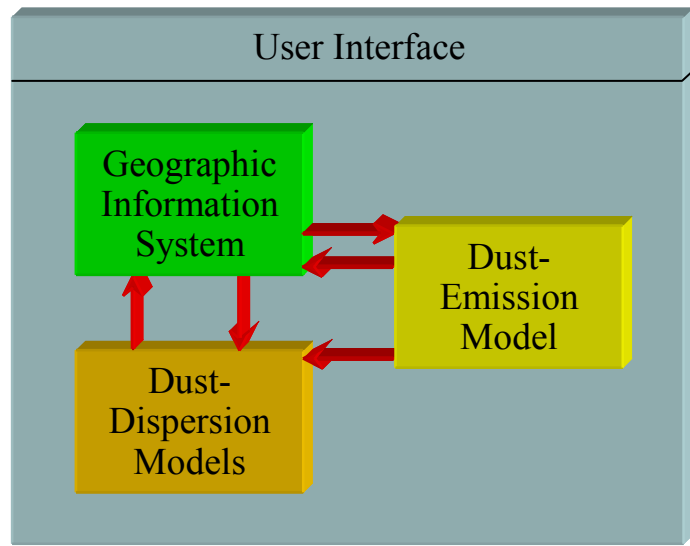


Figure 4.1. Primary Overview of DUSTRAN

- Specifying model simulation and activity release start times and durations
- Specifying activity details in terms of multiple point, area, and line releases.

The *GIS* output functionality includes the capability to graphically view spatial patterns of ground-level concentration and deposition, including an option to view an animation of these patterns. Additionally, patterns of wind vectors for selected heights above ground can be viewed graphically.

The *dust-emission model* uses vehicular dust-emission factors developed on SERDP project SI-1191 (Gillies et al. 2005a, 2005b) and incorporates the widely used AP-42 emission factors for paved and unpaved roads (EPA 2005). Additionally, wind-blown dust-source strengths are based on current formulations in the scientific literature. The dust-emission model functionality includes creating release rates for dust-generating activities of wheeled military vehicles and dust generated from wind erosion.

The determination of emission rates is integrated into the GIS. The user interface includes the capability to graphically define source areas of wind-generated dust as well as area- and line-source characteristics (such as type, speed, and number of vehicles) associated with vehicle-generated dust emissions. DUSTRAN also allows the user to simulate the dispersion and deposition for varying particle sizes and release rates specified through the user interface. Dispersion and deposition can also be simulated for user-specified gases.

The *air-dispersion models* implemented in DUSTRAN are the EPA-approved CALPUFF model (Scire et al. 2000a) and the widely used CALifornia photochemical GRID (CALGRID) model (Scire et al. 2000b). The functionality of the DUSTRAN implementation of these air-dispersion models includes:

- Easy selection of single or multiple station meteorology
- Use of temporally and spatially varying wind fields
- Air-flow models accounting for terrain influences
- Accounting for wet and dry deposition processes
- Typical simulation periods of a few hours to a few days
- Consideration of multiple particles size ranges in a single simulation
- Ability to specify combinations of receptor grids, including polar grids for point sources and specialized rectangular grids for area sources.

The CALGRID model is used for wind-blown dust simulations because the entire modeling domain is a potential source of dust, necessitating the use of a grid model for computational efficiency. For simulating dust dispersion and deposition from various specific point, line, and area sources, the CALPUFF model is used, giving better definition of near-source (within 1 km) impacts.

A diagnostic meteorological model, called the CALifornia METeorological (CALMET) model (Scire et al. 2000b) is also integrated in DUSTRAN. The main function of CALMET is to create gridded fields of wind and boundary-layer parameters from observed meteorological data. These gridded fields are then supplied to the CALPUFF and CALGRID dispersion models, which perform the plume advection, diffusion, and deposition calculations. Figure 4.2 shows the linkages of these dust-dispersion models within DUSTRAN.

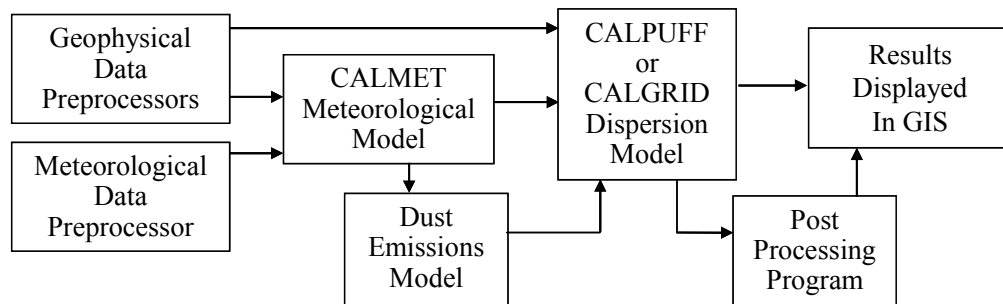


Figure 4.2. Dispersion-Model Components Within the DUSTRAN Modeling System

Numerous data preprocessors interface CALMET, CALPUFF, and CALGRID to routinely available terrain elevation and land-use datasets for use in model calculations. A post-processing program is also available for computing average concentration and deposition values. The DUSTRAN interface dynamically links all the model components. Table 4.1 lists the version numbers for the model components as implemented in DUSTRAN 1.0.

Table 4.1. Version Numbers for Model Components Implemented in DUSTRAN 1.0

Component	Purpose	Version Number
CALPUFF	Dispersion Model	5.5
CALGRID	Dispersion Model	1.6
CALMET	Meteorological Model	5.2
CALPOST	Post-processing Program	5.2
TERREL	Terrain Preprocessor	2.1
CTGPROC	Land Use Preprocessor	1.2
MAKEGEO	Merges Terrain/Land Use Datasets	1.1
READ62	Meteorological Preprocessor for Extracting Standard Upper-Air Formats	4.0

The following sections provide a brief technical overview of the DUSTRAN model components. Numerous documents (e.g., Scire et al. 1989; Scire et al. 2000a; Scire et al. 2000b) discuss the theoretical and technical basis of the dispersion and meteorological models used within DUSTRAN; readers are referred to these documents for detailed information on CALPUFF, CALGRID, and CALMET. An overview is provided here of these model components and their integration within the DUSTRAN framework. A more detailed discussion of the module for vehicular and wind-blown dust-emission factors is given in Section 4.6, which is the technical documentation and reference for this component.

4.2 CALMET

CALMET is a diagnostic meteorological model that generates three-dimensional gridded wind fields and two-dimensional fields of boundary-layer parameters. Surface and upper-air meteorological observations are required to generate the gridded fields. These data are supplied through the “Meteorology” tab within DUSTRAN.

Table 4.2 lists required meteorological observations used by CALMET. The surface data are hourly observations whereas the upper-air vertical profiles are required less frequently, normally twice daily (00Z and 12Z). Multiple surface and upper-air stations may be used, and the stations are not required to be on the DUSTRAN domain. CALMET can interpolate the data to the domain. These input meteorological data are written to formatted surface and upper-air files by the DUSTRAN interface for use in CALMET.

Table 4.2. CALMET Meteorological Input Requirements

Surface Data (Hourly)	Upper Air Data (Twice-daily)
Wind Speed and Direction	Wind Speed and Direction
Temperature	Temperature
Cloud Cover	Pressure
Ceiling Height	Elevation
Surface Pressure	
Relative Humidity	

CALMET also uses geophysical data to derive the gridded meteorological fields. These data (terrain elevations and land-use/land-cover) are routinely available in datasets from the U.S. Geological Survey with varying spatial resolution. In DUSTRAN, terrain data are supplied through GTOPO30 files, which are digital elevation models (DEMs) with a horizontal spacing of 30 arc seconds (approximately 1 kilometer). Land-use/land-cover data are supplied through global-land-cover characteristics (GLCC) files and are of similar resolution.

Preprocessing programs interface the geophysical datasets with the CALMET meteorological model. These preprocessors, shown in Figure 4.3, are implemented within DUSTRAN to automatically extract the required geophysical data based on the user's domain size. The extracted data are used in the CALMET model formulations and are also written to the CALMET output file for use in the CALPUFF and CALGRID dispersion models.

An input file called "Calmet.inp" largely controls the procedures that CALMET uses to derive the gridded meteorological fields. The input file is a text file with a series of keywords that are logically grouped based upon their overall function within CALMET. Every site in DUSTRAN has a "StaticData" directory that stores the template Calmet.inp to be used for that site. The template file is merged with user-input from the DUSTRAN interface before running the model. The parameter settings within the template file are set to optimized values to produce the most realistic output. Caution should be exercised if the user wishes to change any setting within the template file, as unrealistic results may be produced.

The following subsections provide an overview of the CALMET procedures for deriving gridded meteorological fields using the meteorological and geophysical input datasets defined previously. Technical formulations are not provided here because they are available in the CALMET User's Guide (Scire et al. 2000b); instead, the CALMET processing and creation of gridded meteorological fields are described qualitatively.

4.2.1 CALMET-Derived Wind Field

CALMET uses a two-step process to create the three-dimensional wind field for each hourly time step. In step one, an "initial guess" wind field is modified for terrain effects. In step two, surface and upper-air observations are merged objectively with the step-one, terrain-adjusted winds to create the final flow field. Each step is briefly discussed below.

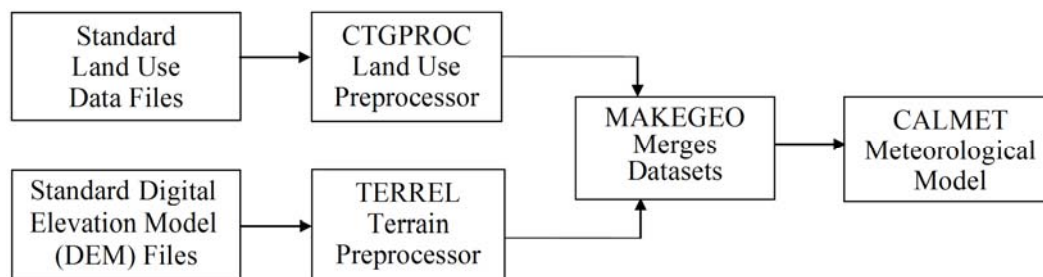


Figure 4.3. Data Flow and Geophysical Preprocessors for CALMET

4.2.1.1 Step-One Wind-Field Formulation

The step-one wind-field formulation begins with an “initial guess” wind field. The initial guess field can be a spatially varying or a constant, domain-mean wind used throughout the grid. In DUSTRAN’s implementation of CALMET, the initial guess wind field is spatially varying and is based on surface and upper-air observations. The surface observations are extrapolated vertically using a power-law or relationships developed from Monin-Obukhov (M-O) similarity theory (e.g., Geernaert 1990), assuming a neutral boundary layer, with M-O extrapolation used by default. The vertically extrapolated surface winds are then merged with the upper-air observations at each node on the grid using a $1/r^2$ interpolation. During the merging, a bias can be applied at each vertical level in the domain, whereby the relative weighting of the surface and upper-air data can be controlled. This level-by-level bias allows for surface data to more greatly influence the flow field in the lowest layers and the upper-air data to dominate the higher layers.

Once the initial guess field has been created, it is adjusted for terrain effects. CALMET has the option of adjusting the wind field for kinematic effects, slope flow, and flow blocking. Each option can be explicitly treated, and the cumulative effects are merged with the initial-guess field to determine the step-one flow field.

1. Kinematic effects are calculated by assuming an initial zero vertical velocity in the first-guess wind field. The vertical velocity is then calculated because of topographic effects, and the horizontal velocity is adjusted using a divergence minimization scheme that iteratively adjusts the horizontal wind components until the three-dimensional divergence is less than a specified value.
2. Slope flow effects, such as upslope flows during the day or drainage flows at night, are based on an empirical scheme that is a function of the terrain slope, distance to the crest, and the sensible heat flux. A separate formulation for the sensible heat flux is used for the daytime and nighttime in CALMET and is performed for overland locations only.
3. Flow blocking, which is the result of stable stratification, is determined by calculating the Froude number for each grid node in CALMET. If a critical Froude number is not exceeded, then the flow is blocked by terrain and is adjusted horizontally tangent to the land feature (i.e., the flow is forced around the land feature).

Of the three terrain-adjustment procedures, the kinematic effects can sometimes lead to unrealistically large horizontal velocities, particularly in complex terrain. Therefore, the kinematic adjustment is not implemented in DUSTRAN.

4.2.1.2 Step-Two Wind-Field Formulation

The step-two formulation is an objective merging of the terrain-adjusted, step-one wind field with surface and upper-air observations. The objective analysis is performed level-by-level by first extrapolating the surface wind observations vertically using a constant power-law or M-O as a function of stability. Then, for a given level, observations that are within a specified radius are weighted equally with the step-one wind field. All other observations at that level have a $1/r^2$ weighting out to a specified radius of inclusion. The radii for equal weighting and inclusion can be specified separately for the surface and all other vertical levels.

Each level of the merged wind field is then smoothed, and the divergence at each grid cell is calculated to provide a new estimate of the vertical velocity. The vertical velocity for the top level of the domain can be set to zero (called the O'Brien adjustment procedure), and the horizontal wind components are readjusted to be mass consistent with the new vertical velocity field using a divergence minimization procedure. The resulting wind field is the final wind field that is output by CALMET for use in the CALPUFF or CALGRID dispersion calculations.

4.2.2 CALMET-Derived Boundary-Layer Parameters

CALMET contains a micrometeorological model that is based upon an energy-balance method, whereby the sensible heat flux is calculated at each grid node by parameterizing the unknown terms—latent heat flux, anthropogenic heat flux, ground storage/soil heat flux, and net radiation—in the surface energy-balance equation. Once the sensible heat flux is calculated, gridded fields of other boundary-layer parameters that are functionally dependent on the sensible heat flux, such as the Monin-Obukhov (M-O) (similarity theory) length and surface friction velocity, are computed.

CALMET has various formulations for calculating the mixing height, which are based upon time of day and stability classification. For unstable, daytime conditions, the mixing height is thermally driven, and so it is a function of the surface heat flux and the vertical temperature profile from upper-air soundings. For stable, nighttime conditions, the mixing height is mechanically driven, and so it is functionally dependent upon the friction velocity.

Because of the explicit use of the surface energy balance method in CALMET, all DUSTRAN simulation start times must start after midnight and before sunrise. CALMET contains time-validation routines that mandate a start time of 5 a.m. local time or earlier. So, if a noon-time or evening release is desired, the simulation start time must begin by 5 a.m., even though the source release time may not occur until much later in the day. Normally, this is of little consequence, as the model runtime is extremely fast and efficient.

4.2.3 Meteorological-Data-Input Options

DUSTRAN allows the user to specify the following four sources of meteorological data to be used by CALMET:

1. *Available Data:* Use available site-specific meteorological data where the data format is known by DUSTRAN, and data-ingest utilities are available in DUSTRAN. Currently, this feature applies to data from DOE's Hanford Meteorological Monitoring Network (within DUSTRAN's "Yakima" site; included with the DUSTRAN install) and data from DoD's Fort Irwin National Training Center meteorological network (within DUSTRAN's "Ft. Irwin" site; not included with install). This is a special option that requires the DUSTRAN code to be modified for implementation at other sites. Any user wishing to use meteorological data from special networks will need to contact PNNL for modifying DUSTRAN to read the specific data format. Another option for using site-specific meteorological data in DUSTRAN is to use CALMET utilities described in CALMET documentation to produce files in the format read directly by CALMET. These

meteorological data can then be used by DUSTRAN with Option 3, *User Defined*, described below.

2. *Single Observation*: Use single-point meteorological observations specified in DUSTRAN through an input window. DUSTRAN creates one “surface” data file and one “upper-air” data file from the user input in the format needed by CALMET. The “dummy” stations are located at the center of the modeling domain and are assumed to persist for the duration of the simulation.
3. *User Defined*: Use surface and upper-air meteorological data files (surf.dat and up_1.dat, up_2.dat,... up_n.dat) that have already been prepared for being directly read by CALMET. These files are created outside of DUSTRAN using CALMET utilities.
4. *National Oceanic and Atmospheric Administration (NOAA) Archived*: Use meteorological data archived from web-site-accessible National Weather Service (NWS) surface and upper-air data stations. (*Note*: To use this option, the meteorological data archive application—MetArchiver—must be running to populate the observations database. For more information, see the section on the MetArchiver in Allwine et al. (2006b).)

Of the four methods, Option 2, “Single Observation,” is the only method that relies on manual user input for defining basic meteorological conditions. These inputs are then used by DUSTRAN to construct all required inputs for use in the CALMET model. The other options (1, 3, and 4) are actual data streams coming from defined sources. The methodology used within DUSTRAN to construct the necessary meteorological inputs for CALMET when using “Single Observation” is described in the next section.

4.2.3.1 Single Observation Method

The “Single Observation” option provides the user with a very easy and convenient way to quickly view the effects of various configurations (e.g., multiple sources, long-range transport, nighttime stable flows) on resulting concentration and deposition fields. Even though the single-point meteorological observation persists and is used for the entire simulation, the model-derived meteorological grids will still vary spatially and temporally because they are a function of land use, topography, and the surface-sensible heat flux (i.e., time of day). CALMET contains a solar model for use in determining sensible heat flux (which drives diffusion rates and mixing-height growth) as a function of time.

The user specifies wind speed, wind direction, mixing height, ambient temperature, relative humidity, ambient pressure, and atmospheric stability through the DUSTRAN meteorological input window. CALMET also needs other surface quantities for completeness: ceiling height, opaque sky cover, and precipitation code, which are specified near the start of the Cal.par DUSTRAN setup file. The Cal.par is a static text file that is used to initialize certain parameters in DUSTRAN. The file can be edited in a standard text editor. However, because it allows many features of DUSTRAN to be controlled, caution should be exercised if modifications to this file are desired. The default values in Cal.par for ceiling height, opaque sky cover, and precipitation code are 100 (units are hundreds of feet), 0 (units are tenths of coverage), and 0 (no precipitation), respectively. The default values for the meteorological variables specified through the DUSTRAN user-input window are also given in the Cal.par file. All user-specified

and default values are provided in the units required by CALMET, and any necessary unit conversions are handled within CALMET.

CALMET requires at least one upper-air sounding location for operation. Using the single observation data entered by the user and parameters listed in the Cal.par file, DUSTAN automatically generates an upper-air sounding file, which is used by the CALMET model. The sounding data consist of pressure, temperature, wind speed, and wind direction at several heights where the lower and upper heights and the number of heights are specified in the Cal.par file. The height spacing is logarithmic to allow narrower spacing close to the surface. For simplicity, the wind direction is assumed constant with height, and the wind speed is assumed to increase with height using the power-law relationship:

$$U_n = U_1 \left(\frac{Z_n}{Z_1} \right)^P \quad (4.1)$$

where U_n = wind speed at sounding height “n” (m s^{-1})
 U_1 = wind speed at lowest sounding height (m s^{-1})
 Z_n = sounding height “n” (m)
 Z_1 = lowest sounding height (m)
 P = power-law exponent depending on atmospheric stability.

The power-law exponents in Equation 4.1 follow from Turner (1994) as given in his Table 4.6 and are listed in the Cal.par file for application of DUSTAN in either “rural” or “urban” areas. The temperature sounding is developed from temperature lapse rates specified as a function of stability in the Cal.par file and the surface temperature specified in the user-input window. Consequently, the temperature sounding is determined as:

$$T_n = T_1 + T_{LR}(Z_n - Z_1) \quad (4.2)$$

where T_n is the temperature at sounding height “n” ($^{\circ}\text{K}$), T_1 is the temperature at the lowest sounding height ($^{\circ}\text{K}$), and T_{LR} is the temperature lapse rate depending on stability (deg m^{-1}).

The atmospheric pressure as a function of sounding height is determined from the hydrostatic relationship as:

$$P_n = P_1 \text{ EXP} \left[- \frac{a(Z_n - Z_1)}{(T_n + T_1)/2} \right] \quad (4.3)$$

where P_n is the pressure at sounding height “n” (mb), P_1 is the pressure at the lowest sounding height (mb), and a is $0.0342 \text{ } ^{\circ}\text{K m}^{-1}$.

4.3 CALPUFF

CALPUFF is one of two dispersion models that are implemented in DUSTRAN. The model is ideal for simulating releases from discrete source-type configurations, such as point, line, and area sources, and is activated by setting the “Simulation Type” to “Source Emissions” within the DUSTRAN interface. The latter two sources—area and line—are integrated with a dust-emission model and can simulate particle dispersion and deposition from paved or unpaved roadways due to various vehicle types.

As the name implies, CALPUFF is a puff model; it transports and diffuses source material as a series of discrete puffs using gridded meteorological fields from CALMET. The model calculates average plume concentration and deposition flux values at defined receptor locations. The receptor field is automatically defined and created by DUSTRAN, based upon the model domain size and source-input configuration.

The use of spatially varying meteorological fields makes CALPUFF ideal for medium- and long-range transport applications where domain sizes often exceed 50 kilometers, and the assumption of “spatially homogenous” meteorology used in straight-line plume models often fails. As a result, CALPUFF has gained widespread acceptance and recently has been approved as a regulatory model (40 CFR Part 51, Appendix W) by EPA for applications involving long-range transport. In DUSTRAN, domain sizes are often on the order of 20 to 400 km; thus, CALPUFF is an appropriate selection for use in the modeling system.

The procedures that CALPUFF uses to define plume transport and dispersion are controlled largely by an input file called “Calpuff.inp.” The input file is a text file with a series of keywords that are logically grouped based upon their overall function within CALPUFF. Every site in DUSTRAN has a “StaticData” directory that stores the template Calpuff.inp to be used for that site. The template file is merged with user input from the DUSTRAN interface before running the model. The parameter settings within the template file are set to optimized values to produce the most realistic output.

The sections that follow review some of the more important parameters that are used by CALPUFF to control puff transport and dispersion. Recommendations are made for the various parameter settings and are based upon experience, guidance documents (e.g. Irwin 1998), and CALPUFF’s specific implementation within the DUSTRAN system. Caution should be used if the user wishes to change any setting within the template file, as unrealistic results may be produced.

4.3.1 Near-Field Release Approximation

Puff models are often computationally restrictive when used for near-field applications involving continuous releases because the puffs are still relatively small, and so enough puffs must be released to approximate the source. In addition, sampling problems may arise near the source if too few puffs are released in a given time-step, especially during rapidly varying meteorological conditions. To address these issues, CALPUFF can use an elongated puff, called a slug, to approximate the release. As the slug is transported downwind and its crosswind dimensions become larger because of dispersion, CALPUFF can transition the slug back to a

puff. The slug method is an input parameter set in the CALPUFF input file and is recommended for use in DUSTAN applications.

4.3.2 Dispersion Coefficients

CALPUFF is a Gaussian model and therefore approximates atmospheric diffusion by specifying dispersion coefficients. The dispersion coefficients are a function of atmospheric stability and affect the vertical and lateral growth of a puff as it is transported downwind. CALPUFF provides many methods for defining the dispersion coefficients, including:

- Direct measure of the horizontal and vertical velocity variances
- Similarity theory formulations
- Pasquill-Gifford-Turner (PGT) specifications (Turner 1994).

Of the listed methods, the similarity-theory formulations are recommended in DUSTAN because the parameters used in their formulation are explicitly calculated by CALMET.

4.3.3 Plume Rise

CALPUFF can account for plume rise, especially from point sources, which are often used to approximate releases from stacks. With stack-type releases, plume buoyancy (due to increased exhaust temperature) and momentum (from exhaust flows) can loft plumes into the air. Plume lofting can result in a phenomenon called “partial plume penetration,” whereby part of the plume is ejected into a stable layer (called an inversion) above the release. The overall effect of these parameters is to increase the release height and remove material from the initial plume, all of which act to reduce surface-concentration and deposition-flux values downwind of the release, particularly near the source. Because DUSTAN domain sizes tend to be large (e.g., greater than 50 km), these effects play a smaller role and only act to increase computation time. They are not recommended for use unless near-field effects are of concern.

4.3.4 Receptor Grids

Receptors are locations where the model performs concentration and deposition calculations. In CALPUFF, a primary receptor grid is used for calculating values across the entire domain. The grid is Cartesian and has uniformly spaced receptors in the X and Y directions. By default, 50 receptors are specified for both directions, so a 100-km domain, for example, has a receptor spacing of 2 km in the X and Y directions. The number of receptors in the primary grid can be changed within the Cal.par file.

In DUSTAN, secondary receptor grids, or sub-grids, are automatically generated in-and-around sources to increase the resolution of the calculated concentration and/or deposition fields very near the source. These sub-grids are treated as discrete receptors in CALPUFF, and up to 4000 discrete receptors are allowed. For each point source, a polar receptor sub-grid is used. For each area source, a rectangular receptor sub-grid is used. No sub-grid is currently implemented for a line source. The size and resolution of the receptor sub-grids are defined according to parameters set within the Cal.par file.

Figure 4.4 is an example of the various receptor grids implemented in DUSTRAN for a CALPUFF model simulation. Receptors are displayed as blue dots, with the primary Cartesian grid spaced uniformly across the domain and a polar and a rectangular sub-grid centered over their respective source types.

4.3.5 Representing Moving Vehicles as Line and Area Dust Sources

DUSTRAN does not treat the motion of individual vehicles, but rather takes a “bulk” approach to dust emissions from vehicle activities. That is, the dust emissions from all vehicles active on a road segment or within a training area over a specified time are assumed to be released uniformly from the road or area at a constant rate throughout the duration of the activity. Therefore, the input fields on the DUSTRAN “Vehicle Parameters” window should not be interpreted as representing the specific motion of individual vehicles, but rather as a convenient approach for providing the vehicle information needed by DUSTRAN.

As described in Section 4.6.1, the dust emissions from a moving vehicle are proportional to the vehicle momentum (i.e., vehicle weight \times vehicle speed). Therefore, if some vehicles of one type travel at significantly different speeds than other vehicles of the same type, another “vehicle type” will need to be added to the DUSTRAN vehicle list such that the other speed(s) can be specified. Additional vehicles can be specified in DUSTRAN by editing the Cal.par file.

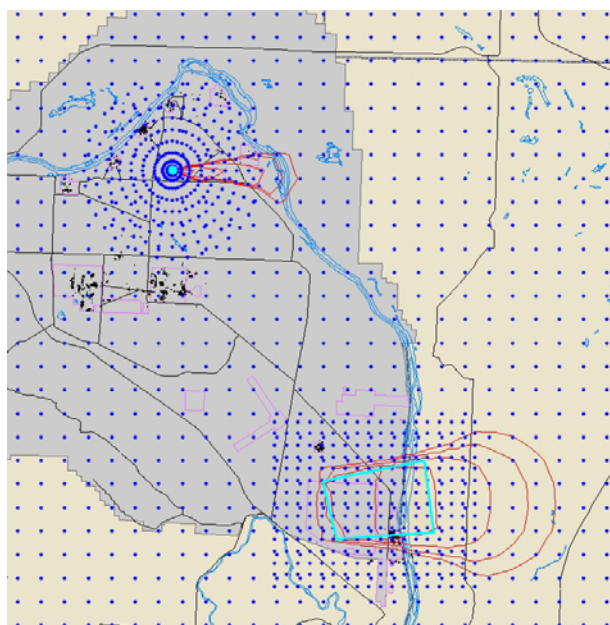


Figure 4.4. Example of the Primary Cartesian Receptor Grid and a Polar and Cartesian Sub-Grid Used Within CALPUFF

4.4 CALGRID

CALGRID is the second dispersion model that is available within DUSTRAN. The model has been implemented to simulate the dispersion of wind-generated dust and is activated by setting the “Simulation Type” to “Wind-blown Dust” within the DUSTRAN interface. In the wind-blown-dust mode, DUSTRAN creates gridded dust-emission factors for the entire model

domain, which are then supplied to the CALGRID model to simulate the downwind dispersion and deposition. The dust-emission factors calculated by DUSTRAN are a function of wind stress, soil texture, and vegetation type across the domain and are discussed further in Section 4.6.2.

CALGRID is a Eulerian model and uses mass continuity to track material throughout a gridded volume. In DUSTRAN, the volume boundaries are defined by specifying a domain in which the user would like to simulate wind-blown-dust dispersion. The amount of dust in a given volume is the sum of dust being generated by the wind or lost by deposition as well as the transfer of dust between volumes through wind transport and atmospheric diffusion. The gridded nature of the model makes it ideal for examining releases from large areas, such as wind-blown dust over a large domain.

The CALMET-derived spatially and temporally varying meteorological fields are used in CALGRID to transport and diffuse material throughout the domain. Horizontal transport requires the two-dimensional gridded fields of the velocity components (U and V) for each vertical layer. Terrain-following vertical velocities are used to determine the vertical transport through each of the vertical cell faces in CALGRID. Horizontal diffusion is a function of the CALMET-gridded PGT stability classification, modified for wind speed within each cell and distortion or shear between horizontal cells (Gifford 1976; Pasquill 1976; Turner 1994). Vertical diffusion is calculated from CALMET-gridded similarity fields and is functionally dependent upon the height above ground and stability.

Emissions are introduced into the CALGRID domain depending on the source type. For area sources, which include the model domain for wind-blown dust simulations, emissions are injected into CALGRID using emission layers, with each layer containing a fraction of the total emissions. In DUSTRAN's implementation of CALGRID, area sources have one emission layer, bounded between the surface and 20 meters. For other source types, such as point sources, material is injected into one or more CALGRID layers based on the height of the stack, plume rise due to buoyancy and momentum, and the plume overlap with the model layers.

The procedures that CALGRID uses to define plume transport and dispersion are controlled largely by an input file called "Calgrid.inp." The input file is a text file with a series of keywords that are logically grouped based upon their overall function within CALGRID. Every site in DUSTRAN has a "StaticData" directory that stores the template Calgrid.inp to be used for that site. The template file is merged with user input from the DUSTRAN interface before running the model. The parameter settings within the template file are set to optimized values to produce the most realistic output. Extreme caution should be used if the user wishes to change any setting within the template file, as unrealistic results may be produced.

4.4.1 Receptor Grid

In CALGRID, the primary receptor grid is Cartesian and has uniformly spaced nodes in the X and Y directions. The nodes serve to both define the horizontal extent of a given cell and specify receptor locations where concentration and deposition values are calculated. Because CALGRID is a Eulerian model, inherent problems exist for situations when the horizontal grid cell size is small and the wind speed is large, as material may be transported through more than

one grid cell in a single time step. To minimize this possible issue, 20 nodes in the X and Y directions are recommended and are set as the default. Therefore, for a 100-km grid, for example, the cell size (and receptor spacing) is 5 km. The number of nodes in the primary grid can be changed within the Cal.par file.

It should be noted that the outer-band of grid cells in CALGRID serve to initialize the inner grid cells within the domain. These cells are considered “boundary cells” and serve as storage locations for the lateral boundary conditions of the grid; no calculations (e.g., transport, diffusion, deposition) are performed within these cells, and so no values are available for contouring. Therefore, the number of receptors in the X and Y directions available for contouring will always be two less than the actual number of nodes.

4.5 CALPOST

The CALifornia POST-processing program (CALPOST) is designed to interface with and summarize the output from the CALPUFF or CALGRID models. In DUSTRAN, the CALPOST post-processing module is used to create user-specified time-averaged values from standard hourly outputs generated by the models. In addition, CALPOST is used to create “Top 50” tables, which are tabular values of the highest 50 concentration and deposition values during a simulation for the averaging period of interest. The averaging periods are set within the DUSTRAN interface; currently, 1, 3, 8, and 24 hour averages are available as well as averages calculated for the length of the run. CALPOST can also be run independently of DUSTRAN using results from DUSTRAN to provide a wider range of output products than are accessible through the DUSTRAN interface.

4.6 Dust-Emission Model

Dust is injected into the atmosphere through active and natural processes. Active processes primarily involve human activity that directly disturbs the surface—for example, vehicle activity on dirt roads and other unpaved areas or from resuspension of loose material covering paved roads. Natural processes include wind erosion, which occurs primarily in arid or semiarid environments and may be enhanced by soil disturbance following recent human activity or following natural disasters, such as range fires. The dust-emission module that is incorporated into DUSTRAN accounts for both vehicular and wind-blown dust-generation processes.

4.6.1 Emission by Vehicular Activity

The vehicular dust-emission module represents dust emissions as the product of an empirically formulated emission factor and the vehicle activity, the latter taken as the total vehicle distance traveled (summed if there are multiple vehicles) in a given period of interest. Explicitly, it can be written as

$$F_j = E_j \cdot A \quad (4.4)$$

where F_j = dust emission due to vehicle activity for particulate size class j [g]
 E_j = emission factor for particulate size class j [g/VKT]
 A = vehicle activity [VKT]
VKT = vehicle kilometers traveled.

The relations that are used to determine E_j are entirely empirical and are usually available for only some of the standard particulate size classes (e.g., PM_{2.5}, PM₁₀, PM₁₅, and PM₃₀). Variables on which various authors have expressed an E_j dependency include the silt content of the surface, the number of vehicle axles, vehicle weight, vehicle speed, and soil moisture. The emission factor, E_j , is determined as a product of some combination of these variables, each raised to an empirically determined power and a fitted constant. The paved- and unpaved-road emission factors in EPA's AP-42 (EPA 2005) are based on this approach and are available for use in DUSTRAN.

Emission factors have been measured for specific vehicles or classes of vehicles. The particulate emission factors for wheeled military vehicles used in DUSTRAN were provided through SERDP research projects. In observations carried out using a variety of wheeled vehicles (primarily military) at Ft. Bliss, Texas, Gillies et al. (2005a, 2005b) found that the only two variables that matter significantly in calculating the PM₁₀ emission factor for unpaved roads are vehicle weight and vehicle speed. Moreover, when weight and speed are properly accounted for, a single empirically derived functional form may be used to calculate a vehicle-specific emission factor. This function may be expressed using

$$E_{PM10} = 0.003 \cdot W \cdot S \quad (4.5)$$

where W is the vehicle weight (kg), and S is the mean vehicle speed (km/h).

Combining Equations 4.4 and 4.5 and summing over the types of vehicles operating on an unpaved road of length, L , during time period, T , gives the total emission from the road for that time period as:

$$F_{PM10} = 0.003 \cdot \sum_{i=1}^k W_i \cdot S_i \cdot A_i \quad (4.6)$$

where i = vehicle type (e.g., Humvee; specifies vehicle weight)
 k = total number of vehicle types
 $A_i = L \cdot N_i$
 N_i = total number of vehicles of type i .

The DUSTRAN vehicle-activity dust-emission module produces total emissions for each road segment over the time period, T . Vehicular dust emissions are then passed to the CALPUFF dispersion model where they are released into the modeling domain uniformly along each road segment in both space and time for the duration of the activity.

The vehicle-emission module requires the Universal Transverse Mercator (UTM) easting and northing coordinates to describe the starting and ending points of each road segment as well as the activity duration. Within DUSTRAN, the roadways are created graphically by drawing each segment within the ArcMap map window. For a given line segment, DUSTRAN prompts the user to enter the weight and mean speed for various vehicle types traveling on the roadway. For paved surfaces, emission factors are based on EPA AP-42 recommended values (EPA 2005) and are available for $PM_{2.5}$, PM_{10} , PM_{15} , and PM_{30} . For unpaved road surfaces, the user has the option of specifying whether to use emission factors derived from EPA AP-42 (EPA 2005) or from Gillies et al. (2005a, 2005b). Because the Gillies et al. (2005a, 2005b) work is specifically for $E_{PM_{10}}$, emission factors for other size classes under this option are estimated by computing the ratio of Gillies et al. $E_{PM_{10}}$ to EPA AP-42 $E_{PM_{10}}$ and applying this ratio to values for EPA AP-42 unpaved road $E_{PM_{2.5}}$ and $E_{PM_{30}}$ particle class sizes. As of this writing, AP-42 does not include recommendations for unpaved road PM_{15} emission factors; PM_{15} emissions under both options are thus estimated via a linear interpolation between PM_{10} and PM_{30} emissions. Average fleet weight and average fleet speed, required for AP-42 formulations, are calculated automatically from information input by the user in the DUSTRAN interface.

During military training exercises, off-road activities can occur within specific training areas where numerous vehicles can move around the area (both on-road and off-road) during a period of time where the specific paths of the vehicles are not known. DUSTRAN treats this area-wide training activity as an area source. The total area-wide dust emissions for each particle-size range during the period of the training are determined using the same method as for roads described above. Knowing the total distance traveled by each vehicle type during the training period, the total dust emissions for each particle-size range are determined using the emission factors described above for unpaved roads. No distinction is made between dust emissions from vehicles operating on unpaved roads versus vehicles operating during off-road maneuvers. At this time, dust-emission factors for off-road activities are not available, and the assumption is made that emission factors for unpaved roads are a reasonable surrogate to off-road vehicular activities.

4.6.2 Windblown Dust

The windblown dust formulation in DUSTRAN provides a measure of the dust emission from the modeling domain caused by wind erosion of the surface. These emissions are a function of the surface wind stress, vegetation class, and soil texture across the modeling domain. The surface wind stress, as approximated by the friction velocity, is calculated as a function of time and location from the CALMET meteorological model. Vegetation class and soil-texture coverage are obtained from well-established global databases and are discussed further in Sections 4.6.2.3 and 4.6.2.4, respectively.

The “Add Site Wizard” within DUSTRAN automatically creates vegetation-class and soil-texture files for use in a wind-blown dust simulation whenever a new site is created. These characteristic files, which are a subset of the original global datasets, can be used for any domain specified within a site and are the default files that are used for generating dust emissions in a wind-blown-dust simulation. Additionally, the user has the option of specifying finer-resolution characteristic files, and these files can be ranked in their order of use in a given simulation.

When used in this way, high-resolution files can provide detailed information in user-specific regions within the domain, and the default files provide information where there is no user-specified information. High-resolution files can be created using the “Polygon Layer Creator Utility,” which is an easy way to build vegetation class and soil texture files or for exploring the effects of vegetation removal or soil disruption (e.g., off-road vehicle traffic disturbing soils in new areas, field plowing) on dust emissions.

The approach in DUSTRAN for computing PM₁₀ concentrations resulting from wind-blown dust is to first calculate gridded fields of wind-generated dust emissions over the modeling domain for each model time step. These time- and space-varying dust-emission data are then provided to the CALGRID dispersion model, which uses winds from CALMET for transporting, diffusing, and depositing the emitted dust throughout the modeling domain. The wind-blown-dust emissions for each model grid cell are calculated using the method given in the following sections (4.6.2.1 through 4.6.2.4). The principal information needed to calculate the dust emissions for each model grid cell is the time-varying friction velocity (from CALMET), the area-weighted average vegetation mask, and the area-weighted average fraction of total dust emissions by particle-size category for each grid cell.

4.6.2.1 Dust Flux as a Function of Friction Velocity

Numerous authors over the past three decades have made laboratory and field measurements of dust flux from wind erosion and empirically related those measurements to the friction velocity, u_* , which is a measure of wind stress on the surface. There have been some efforts to provide a theoretical foundation for the functional form of the flux in terms of friction velocity, but observations continue to have a great deal of scatter and do not yet validate particular theoretical results. The primary difference among most published relations is whether the flux depends on u_* raised to the third or fourth power. (Shao [2000] notes that measurements in a variety of environments suggest that the vertical dust flux is proportional to u_*^n , where $2 < n < 5$.) Because of their field measurements of dust flux, G ($\text{g cm}^{-2} \text{s}^{-1}$), under a variety of conditions, we have adopted the formulation of Gillette and Passi (1988):

$$G = Cu_*^4 \left(1 - \frac{u_{*t}}{u_*} \right) \quad (4.7)$$

where G = dust flux ($\text{g cm}^{-2} \text{s}^{-1}$)
 C = proportionality constant ($\text{g cm}^{-6} \text{s}^3$)
 u_* = friction velocity (cm s^{-1})
 u_{*t} = threshold friction velocity below which dust emission does not occur (cm s^{-1}).

In addition to the uncertainty in the exponent of u_* , there has also been significant experimental variation in the values of u_{*t} .

Gillette and Passi did not publish values of C and u_{*t} in the above relation. However, they did graphically present a variety of observations of G versus u_* . We digitized the data from

their graph and computed the root-mean-square (rms) difference between the function above and the data for a variety of combinations of C and u_{*f} . These results are shown as a contour plot in Figure 4.5. The figure shows that there is a broad region over which the rms differences are not much different from the absolute minimum value, which occurs near a fitted threshold friction velocity of about 33 cm s^{-1} . We selected compromise values of $C = 1.0 \times 10^{-14} \text{ g cm}^{-6} \text{ s}^3$ and $u_{*f} = 20 \text{ cm s}^{-1}$, which places the threshold friction velocity below the lowest reported value of u_* . Grini and Zender (2004) note that this is a widely cited value for the threshold friction velocity. Figure 4.6 shows the fit with our coefficients.

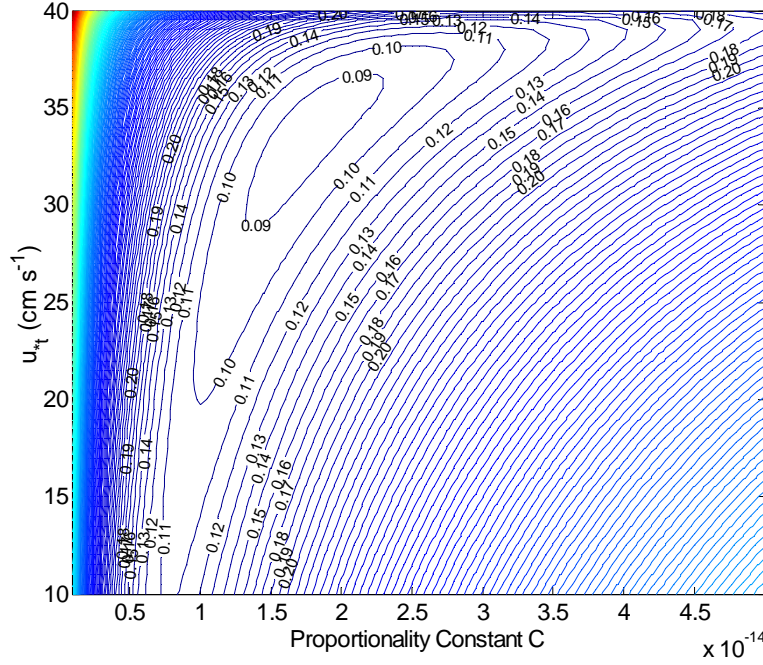


Figure 4.5. Contour Plot of RMS Differences Between Equation (4.7) and Observations of Dust Flux G Discussed by Gillette and Passi (1988)

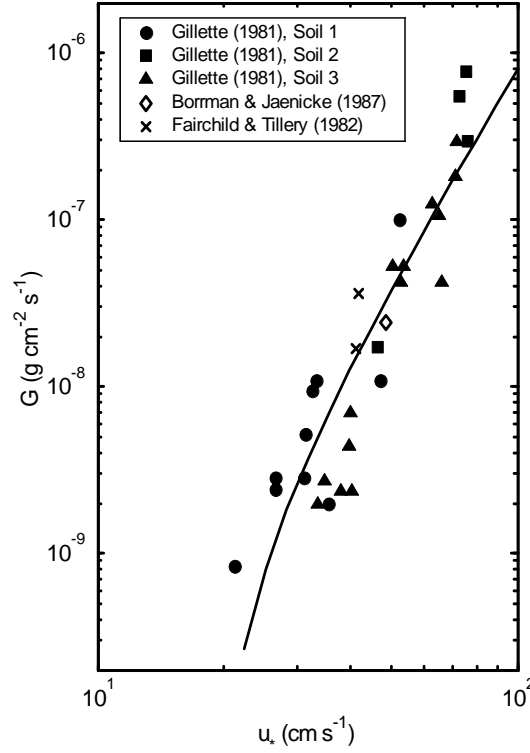


Figure 4.6. Observations of G Versus u^* after Gillette and Passi (1988). The solid line is Equation (4.7) with $C = 1.0 \times 10^{-14} \text{ g cm}^{-6} \text{ s}^3$ and $u_{*t} = 20 \text{ cm s}^{-1}$.

4.6.2.2 Effect of Soil Moisture

Soil moisture, if a measure is available, is taken into account in our approach using the method of Fecan et al. (1999) as cited by Nickovic et al. (2001). The soil moisture is incorporated through a wetness factor, f_w , that multiplies the threshold friction velocity to increase it. Consequently, the total dust flux from the surface accounting for soil moisture is

$$G = Cu_*^4 \left(1 - \frac{f_w u_{*t}}{u_*} \right) \quad (4.8)$$

where the soil wetness factor is given as

$$f_w = \begin{cases} \left[1 + 1.21(w - w')^{0.68} \right]^{1/2} & w > w' \\ 1 & w \leq w' \end{cases} \quad (4.9)$$

In these equations, f_w is the soil wetness factor (dimensionless), w is the gravimetric soil moisture (mass of water/mass of soil, %), and w' is the maximum amount of water that can be adsorbed by the soil (%).

w' is given as a function of the fraction of clay in the soil, β_1 (see Section 4.6.2.4):

$$w' = 14\beta_1^2 + 17\beta_1 \quad (4.10)$$

At this time, soil moisture, w , is not a function of time or location in DUSTRAN, but is currently specified as a constant value in the Cal.par model static file. The default value is zero, leading to a wetness factor of one, which is dry soil.

4.6.2.3 Vegetation Cover Effects on Dust-Emitting Potential

Equation 4.8 gives the maximum wind-generated dust flux from the surface, not accounting for the effects of different types of vegetation cover on dust-emitting potential. Essentially, more vegetation cover results in less wind-blown dust generated from the surface. This effect of vegetation cover on wind-blown dust is treated by simply multiplying the dust flux from Equation 4.8 by a vegetation mask, α , that ranges from zero to one. The total dust flux from the surface accounting for vegetation is then given as

$$G = \alpha C u_*^4 \left(1 - \frac{f_w u_{*t}}{u_*} \right) \quad (4.11)$$

The values of the vegetation mask α are taken directly from the Olson World Ecosystem (Olson, 1992) that defines 59 distinct classes of vegetation. Various measures of vegetation cover (e.g., canopy cover, foliar cover, basal cover, total vegetation versus bare rock or soil) are routinely collected during ecological and remote-sensing studies. This information was used by Olson to assign values of α to each of the vegetation classes; α values are thus included in the Olson database. Of the 59 classes, only four have sufficiently exposed soil to allow for wind erosion, and they include two desert categories and two semi-desert categories. Because of the sparseness of vegetation in deserts, the Olson-assigned α for those categories has a value of 1.0. Because the more widespread shrubs and grasses in the semi-desert categories reduce the fraction of erodible soil area, Olson assigned a value of 0.5 to α for these categories. Table 4.3 lists the Olson identification number, vegetation class description, and α for these four classes. All other Olson vegetation categories have an α value of zero and therefore do not contribute to wind-blown-dust emissions.

Within DUSTRAN, the default Olson-vegetation-class file is derived from the original 10-minute resolution global database at the time of the site's creation. The default dataset can be supplemented or replaced with higher-resolution, Olson-based vegetation class files created by the user using the "Polygon Layer Creator Utility." Such a higher-resolution dataset could, for example, explicitly assign Olson classes with α values of 1.0 to polygons corresponding to unpaved roads, tank/vehicle trails, military firing ranges, burned areas, plowed agricultural fields, or other disturbed surfaces located within larger vegetated regions. Use of such higher resolution datasets would permit estimates of wind-generated dust produced by small-scale domain features that are not spatially resolved in the coarser default vegetation file.

It should be noted that α values for areas with rapidly growing vegetation, such as planted agricultural fields or areas recovering from range fires, will change over time. Our research did not yield any quantitative scientific studies of how α values vary in such situations. However,

for the typical simulation periods of a few hours to a few days for which the DUSTRAN modeling system was designed, it is reasonable to treat assigned α values as constant over the duration of a model run. In such situations, assigning specific Olson vegetation classes and associated α values will depend on the point within the growing cycle (e.g., a freshly plowed field is likely to be assigned a vegetation code with α equal to 1.0 while a field ready for harvesting would be assigned the vegetation code associated with the crop) and should be set in consultation with a biologist or ecologist familiar with both plant-growth cycles and windblown-dust potential.

Table 4.3. Olson Vegetation Classes Used in the Wind-blown Dust-Emission Model

ID #	Olson Vegetation Class Description	α
8	Desert, mostly bare stone, clay and sand	1.0
50	Sand desert, partly blowing dunes	1.0
51	Semi-desert/desert, scrub/sparse grass	0.5
52	Cool/cold shrub, semi-desert/steppe	0.5

The value of α actually used in Equation 4.11 to calculate the dust emissions for a model grid cell is the area-weighted average of α 's for all the vegetation categories that fall within the grid cell. The area-weighted average vegetation mask, $\bar{\alpha}$, is calculated as

$$\bar{\alpha} = \sum_{i=1}^4 f_i^V \alpha_i \quad (4.12)$$

where $\bar{\alpha}$ is the weighted averaged vegetation mask (dimensionless), α_i is the vegetation mask value for the i^{th} Olson vegetation class in Table 4.3 (dimensionless), and f_i^V is the area fraction of the i^{th} Olson vegetation class in a grid cell (dimensionless).

The area fractions for the four Olson vegetation classes will sum to one or less. The sum may be less than one because, as noted previously, many other Olson vegetation classes exist that have α 's equal to zero.

4.6.2.4 Approximating the Size Distribution of Windblown Dust

The formulation given above estimates the total mass of dust produced by wind. However, it is also important to know the size distribution and in particular how much of the dust consists of particles smaller than $10\mu\text{m}$ in diameter. To do this, we have used global databases of soil-texture classes to estimate the fraction of the emitted dust in four separate particle-size ranges. Soil textures are typically defined (Tegen and Fung 1994) in terms of their fractions of clay, small silt, large silt, and sand. Table 4.4 gives typical properties of particles for each soil-texture class.

The approach for determining the soil-texture class (and thus the particle-size distribution) follows from Nickovic et al. (2001) using a Zobler soil-categories database, and Table 4.5 lists the fractions, $\beta_{j,k}$, of the four (k-index) soil texture classes within each of the seven (j-index)

Zobler soil categories. Note that the fractions of soil-texture classes for each Zobler category sum to one. It should also be noted that the size fractions for small and large silt given by Nickovic et al. (2001) were too large by a factor of two. The values in Table 4.5 are corrected.

Table 4.4. Features of Typical Dust Particles (after Nickovic et al. 2001)

k	Soil Texture Class	Range of Particle Diameters (μm)	Typical Particle Diameter (μm)	Particle Density (g cm^{-3})	γ_k
1	Clay	1–2	1.5	2.50	0.08
2	Small silt	2–20	12	2.65	1.00
3	Large silt	20–50	36	2.65	1.00
4	Sand	50–100	76	2.65	0.12

Table 4.5. Fractions, $\beta_{j,k}$, of the Soil-Texture Classes in each Zobler Soil Category

J	Zobler Soil Categories	k=1	2	3	4
		Clay	Small Silt	Large Silt	Sand
1	Coarse	0.12	0.04	0.04	0.80
2	Medium	0.34	0.28	0.28	0.10
3	Fine	0.45	0.15	0.15	0.25
4	Coarse-medium	0.12	0.09	0.09	0.70
5	Coarse-fine	0.40	0.05	0.05	0.50
6	Medium-fine	0.34	0.18	0.18	0.30
7	Coarse-medium-fine	0.22	0.09	0.09	0.60

Currently, the soil-texture category for a desired location in the modeling domain is being read from an ASCII, comma-delimited text file that was derived from the Zobler raster image with a 1-degree resolution (Staub and Rosenzweig 1992). Sources for higher resolution soil textures that are spatially complete (e.g., cover the continental United States) are being investigated for possible inclusion in a future version of DUSTRAN. Additionally, the user has the option of creating high-resolution Zobler soil texture files using the “Polygon Layer Creator Utility.” The user-specific files can be associated with a given simulation to supplement or replace the soil textures derived from the default Zobler global file.

To accomplish the size partitioning of the dust flux from each model grid cell, we use the dust-productivity factor as defined by Nickovic et al. (2001). For each of the four particle-size classes, we define a dust-productivity factor δ_k so that the dust flux in the k^{th} particle-size class, G_k , is

$$G_k = \delta_k G \quad (4.13)$$

where G is from Equation 4.11. The dust-productivity factor for a grid cell is determined by

$$\delta_k = \gamma_k \sum_{j=1}^7 f_j^Z \beta_{j,k} \quad (4.14)$$

where γ_k is the ratio of mass available for uplift to total mass in that soil texture class (size range), $\beta_{j,k}$ is from Table 4.5, and f_j^Z is the area fraction of the j^{th} Zobler soil category in a grid cell. The area fractions for the seven Zobler categories sum to one. Table 4.4 lists the values of γ_k , which are those used by Nickovic et al. (2001). Because the values of δ_k represent a partitioning of the total flux, G , they should sum to unity. However, the values of G used by Gillette and Passi (1988) to develop Equation 4.7 were for particle sizes smaller than 40 μm in diameter. This essentially excludes the larger sand category. This exclusion of the larger sand category is accounted for by using an “enhanced” total dust flux, G' , in Equation 4.13. Therefore, the “actual” dust flux for each particle size (soil texture class) within a grid cell is

$$G_k = \delta_k G' \quad (4.15)$$

where G' is determined as

$$G' = \frac{\sum_{k=1}^4 \delta_k}{\sum_{k=1}^3 \delta_k} G \quad (4.16)$$

Substituting Equation 4.16 into 4.15 gives the actual dust flux by particle size category as

$$G_k = \delta_k \frac{\sum_{i=1}^4 \delta_i}{\sum_{i=1}^3 \delta_i} G \quad (4.17)$$

Currently in DUSTRAN, only the PM_{10} size particles from wind-blown dust are provided as a gridded output. The emission flux of PM_{10} for each grid cell is the sum of the first two particle-size categories, or

$$G_{\text{PM10}} = \sum_{k=1}^2 G_k \quad (4.18)$$

4.6.3 Decision-Support Applications

The current windblown dust module in DUSTRAN provides a practical estimate of dust emissions from the modeling domain caused by surface wind erosion, while the vehicular-activity module provides state-of-the-art estimates of vehicular-generated dust. Preliminary comparisons indicate that DUSTRAN simulations agree well with observations, particularly in

terms of maximum PM₁₀ concentrations likely to be encountered. (See Section 4.8 for more information.) DUSTRAN can be used as a planning and decision support tool by exercising its modules either separately or in combination to provide estimates of dust concentrations. For example, the move-out of large military convoys can generate dust that affects civilian areas surrounding a military installation. Exercising DUSTRAN's vehicular-generated dust module can help identify travel routes least likely to create impacts. DUSTRAN simulations also can be used to determine if simple measures such as modifying convoy speed or moveout start times will sufficiently mitigate any potential impacts, or if more extensive (and expensive) options such as the use of dust suppressants must be considered. Similarly, DUSTRAN can be used to determine if, under a given set of meteorological conditions, proposed military operations in combination with natural wind erosion are likely to produce dust concentrations that will exceed ambient air quality standards. Such applications currently require that the DUSTRAN windblown dust and vehicular-generated dust modules be exercised separately, with the simulated PM concentrations simply added together to estimate total (windblown plus vehicular-generated) dust. DUSTRAN thus can be used to aid "go/no-go" training decisions, and to investigate whether measures such as altering the time of day or the duration of the proposed training are sufficient to mitigate potential air quality impacts.

4.7 Example DUSTRAN Simulation

This example steps through a DUSTRAN simulation for particulate emissions from both a point and an area source. The point source represents particulate emissions from a stack, and the emissions are defined explicitly. The area source represents a region of dust emissions from vehicle activity; these emissions are calculated automatically by the DUSTRAN vehicular dust-emission model. Both sources are set to run for the same duration, and the downwind air-concentration and ground deposition are simulated.

4.7.1 Starting DUSTRAN

DUSTRAN is an integrated dispersion modeling application within the ArcMap (Version 9) GIS interface. To begin a DUSTRAN simulation, open ArcMap. On the ArcMap toolbar, click on the "DUSTRAN" button (see Figure 4.7):

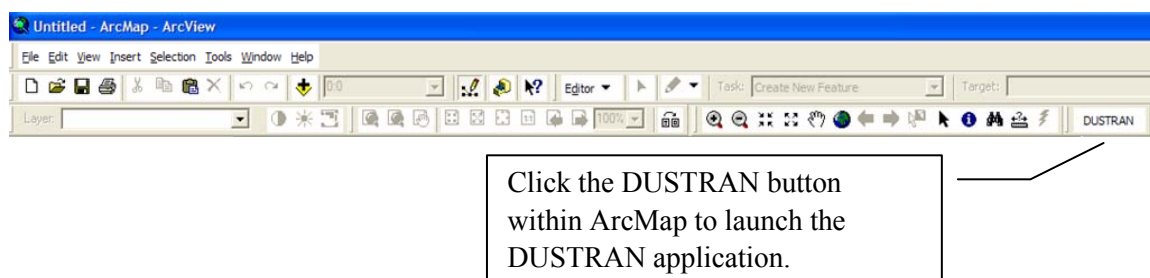


Figure 4.7. ArcMap Toolbar

4.7.2 Selecting a Site

The user interface to the DUSTRAN model will appear in a frame within the ArcMap application (see Figure 4.8). Click the “Select Site...” button to open a dialog box that allows the user to select an existing site:

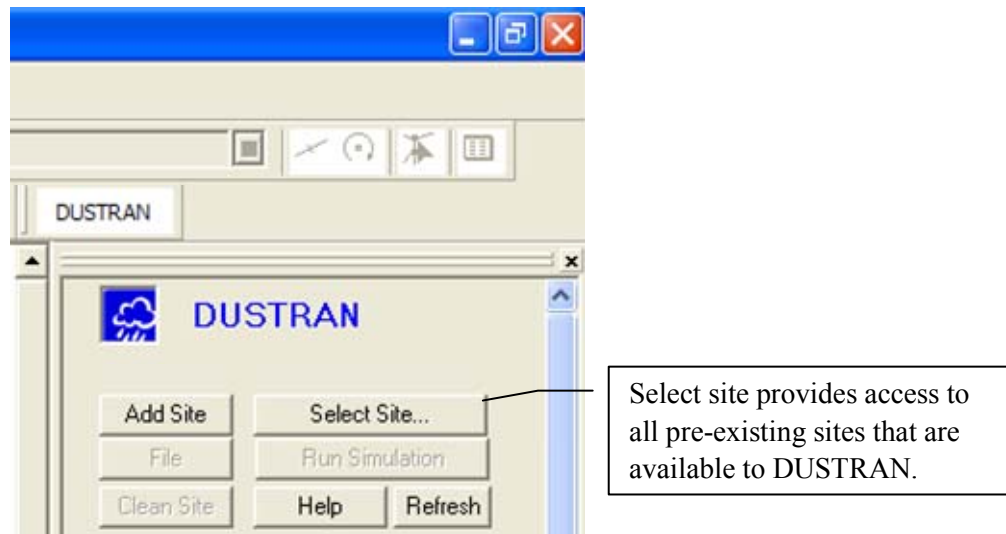


Figure 4.8. DUSTRAN User Interface

Select “Yakima” from the list of available model sites (see Figure 4.9) and then click “Open.”

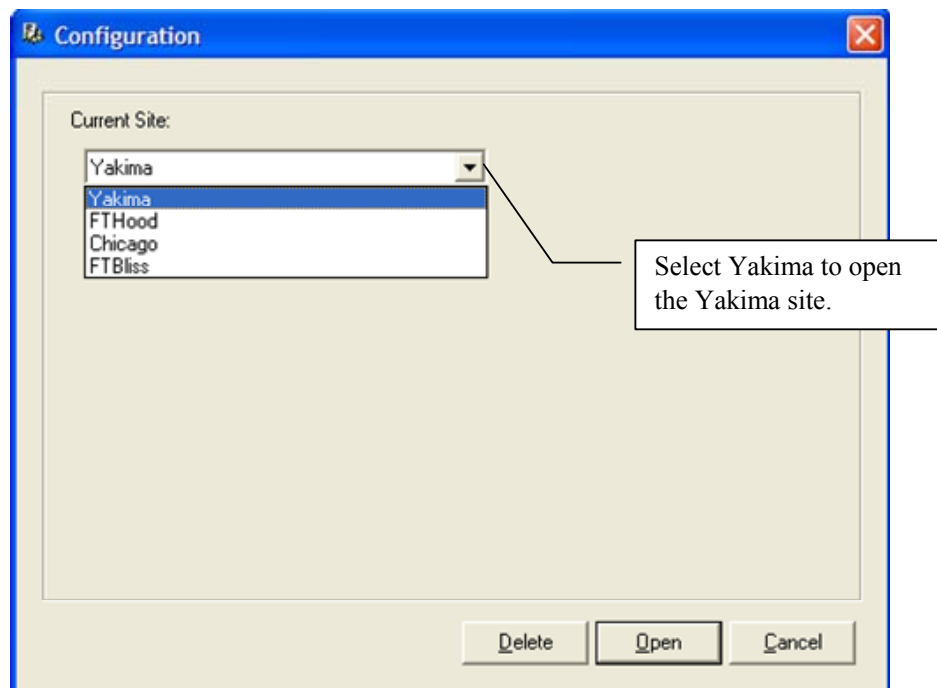


Figure 4.9. Available Model Sites

The Yakima site, which encompasses the DOE Hanford Site, will open within ArcMap. A list of available GIS data layers will appear in the left frame, and DUSTAN-specific input parameters will appear in the right frame (see Figure 4.10).

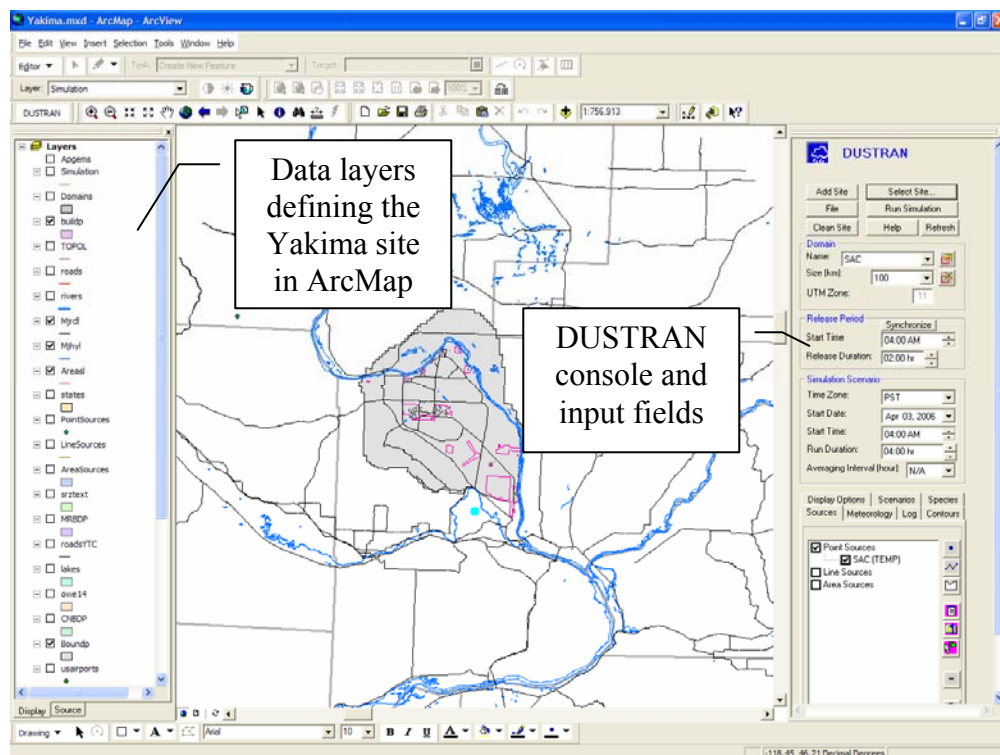



Figure 4.10. DUSTAN “Yakima Site,” Displaying the DOE Hanford Site


4.7.3 Creating a Domain

The first step in setting up a scenario in DUSTAN is to create a domain and set the domain size. A domain is a user-specified area where both meteorological and dispersion model calculations are performed. Click the “New Domain”  button in the “Domain” panel (see Figure 4.11). Then, click on a location (somewhere near the center of the site) in the map window that represents the center of the model domain. In the dialog box that appears, enter the name “Yakima” for the domain and click “OK.”

By default, the domain size is set to 100 km. Set the size from the “Size” listbox in the “Domain” panel to 80 km. The domain should now appear as a shaded, rectangular region bounding DOE’s Hanford area.

4.7.4 Setting the Model Specie

By default, there are four PM species available to model in DUSTAN (see Figure 4.12). This tutorial will model the 10-micron (PM_{10}) specie; uncheck $PM_{2.5}$, PM_{15} , and PM_{30} . Additional

species (particles and gases) can be added using the “Add Species”  button on the “Species” tab, but for this exercise, we will use the existing PM₁₀ species in the list.

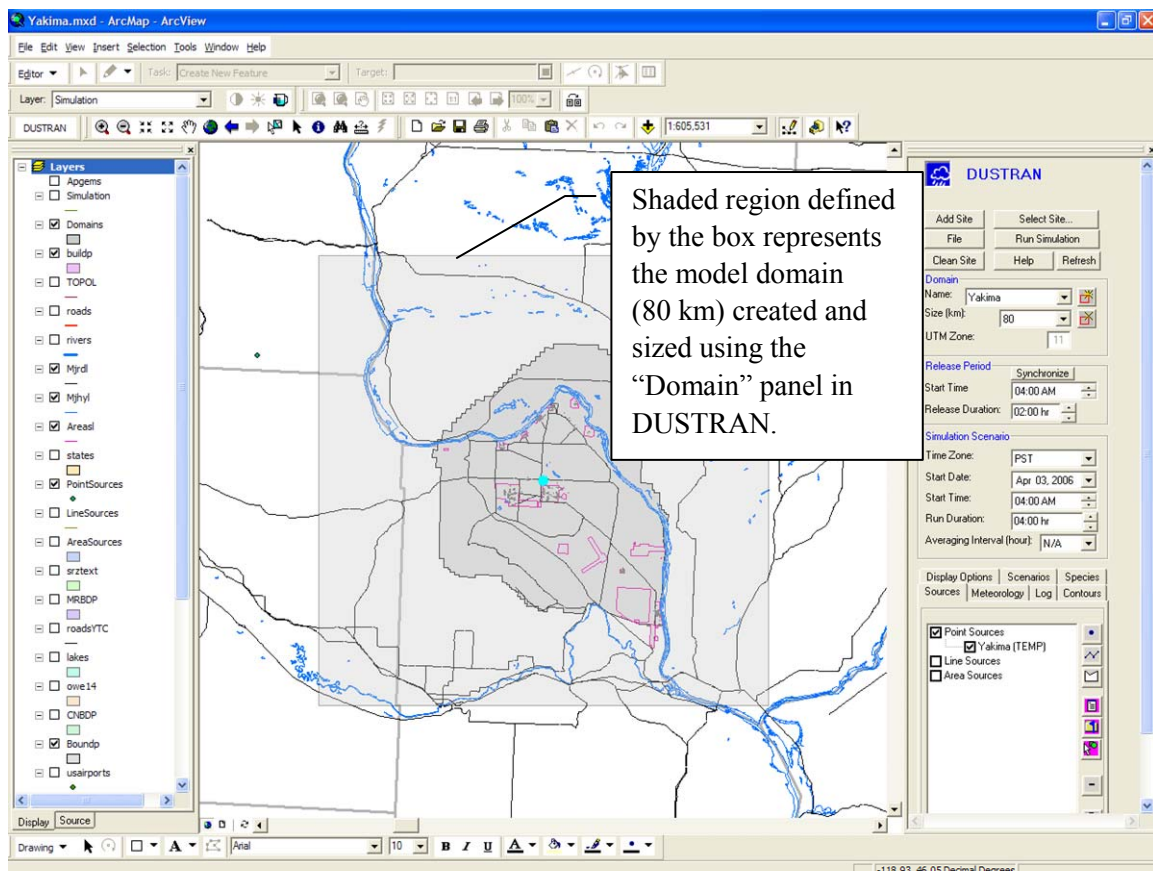


Figure 4.11. Domain Panel

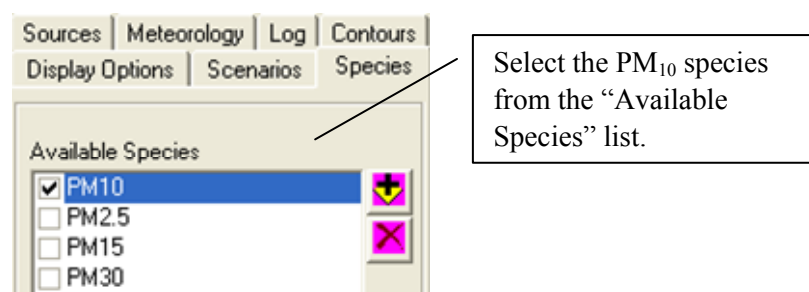



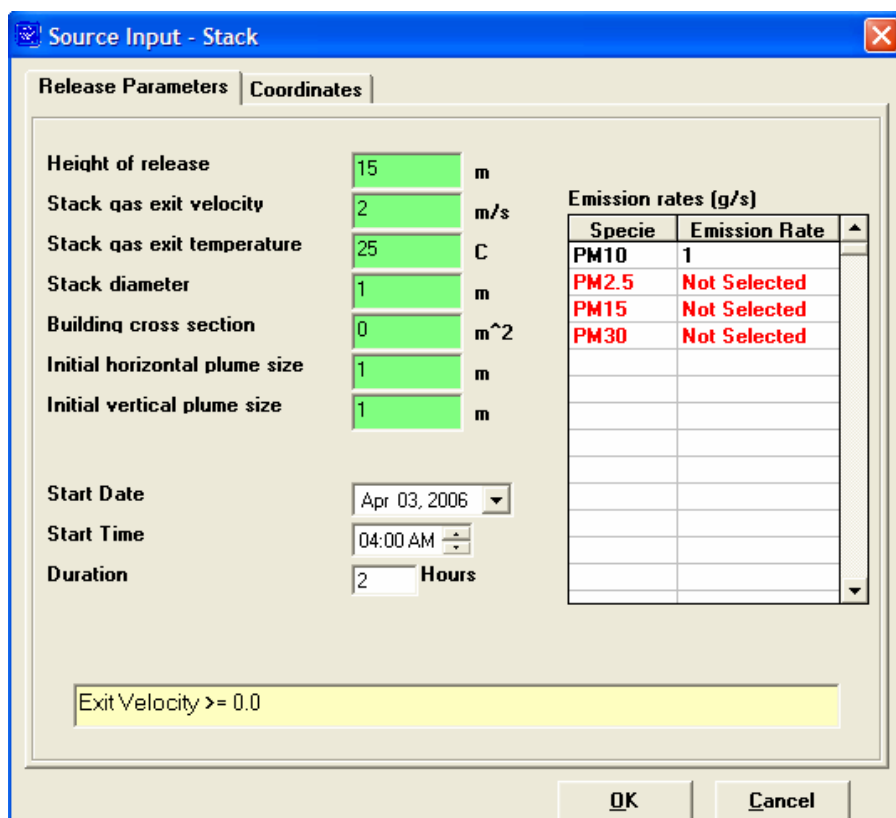
Figure 4.12. Available Species List

4.7.5 Creating a Point Source

Click on the “Sources” tab. Note that there is already a point source called “Yakima” listed under “Point Sources”; this corresponds to the point that is used by DUSTAN to mark the center of the domain. Uncheck the name, and the point will disappear from the center of the domain in the ArcMap map window.

To create a new point source, click on the “Point Source”  button on the “Sources” tab. Click on a location within the domain to place the point source. Call the source “Stack” and click “OK.”

The “Source Input” form for the point source will appear (see Figure 4.13). Enter the “Release Parameters” as follows and click “OK” to continue:




Specie	Emission Rate
PM10	1
PM2.5	Not Selected
PM15	Not Selected
PM30	Not Selected

Figure 4.13. Point Source Input Form

Notice that the new source shows up as a point in the ArcMap map window and also appears in the “Point Source” list on the “Sources” tab.

4.7.6 Creating an Area Source

Next, create an area source by clicking on the “Area Source”  button on the “Sources” tab. An area source can be a triangle or four-sided polygon. It is created by clicking on three or four locations depending on whether one wants a triangle or a four-sided polygon in the ArcMap map window. The final corner should be a “double-click” to complete the polygon. Create the area source by drawing an ≈1-km-square polygon near the center of the domain, enter the source name “Field” and click “OK.”

The “Source Input” form for the area source will appear (see Figure 4.14):

Source Input - Field

Release Parameters | Vehicle Parameters | Coordinates

Field Source Parameters

☐ User Defined ☒ Emission Model

Effective height above ground: 0 m
 Air temperature: 25 C
 Effective rise velocity: 1 m/s
 Effective radius: 1 m
 Initial vertical spread: 1 m

Emission Factor Type: DRI Factors

Start Date: Apr 03, 2006
 Start Time: 04:00 AM
 Duration: 2 Hours

OK Cancel

Figure 4.14. Area-Source-Input Form

For the area source, we will use the “Emission Model” to calculate dust emissions created by a single vehicle using the “DRI Factors” (Desert Research Institute). Vehicular dust emissions are a function of vehicle parameters, such as weight and speed. Click on the “Vehicle Parameters” tab (see Figure 4.15) and specify the following vehicular information:

- The “Distance Traveled” is the total distance traveled by the vehicle within the area. The emissions are assumed to be uniformly distributed over the area and constant for the duration of the release.
- Click “OK,” and the area source will appear in the ArcMap map window and also under the “Area Sources” list on the “Sources” tab (see Figure 4.16).

4.7.7 Entering Meteorological Data

Next, click on the “Meteorology” tab within DUSTRAN and select “Single Observation” from the listbox. The “Specify Meteorological Data” form appears. Enter the meteorological parameters as shown in the form below. Select the “Atmospheric Stability” as “E – Slightly Stable,” which is reasonable for early morning springtime conditions. Also, enter a wind direction from approximately the west-southwest (240 degrees). Figure 4.17 shows the completed form.

The dialog box 'Source Input - Field' has three tabs: 'Release Parameters', 'Vehicle Parameters' (selected), and 'Coordinates'. Under 'Vehicle Parameters', there is a list of vehicles with checkboxes. 'GMC G20 Van' is selected. To the right, the 'Vehicle Description' field contains the text: 'DRI TRAKER vehicle used for measuring dust emissions in real time.' Below this, several parameters are set: 'Number of Vehicles' is 1, 'Vehicle Speed' is 50 km/hr, 'Vehicle Weight' is 3100 kg, 'Polygon Area' is 5.57 km², and 'Distance Traveled' is 5 km. A yellow highlighted box at the bottom contains the text 'Distance Traveled >= 0.0'. 'OK' and 'Cancel' buttons are at the bottom right.

Vehicle	Selected
Dodge Neon	<input type="checkbox"/>
Dodge Caravan	<input type="checkbox"/>
Ford Taurus	<input type="checkbox"/>
GMC G20 Van	<input checked="" type="checkbox"/>
GMC C5500	<input type="checkbox"/>
HMMwV	<input type="checkbox"/>
M923A2 (5-Ton)	<input type="checkbox"/>
M1078 LMTV	<input type="checkbox"/>
M977 HEMMET	<input type="checkbox"/>
Freightliner	<input type="checkbox"/>

Vehicle Description
DRI TRAKER vehicle used for measuring dust emissions in real time.

Number of Vehicles: 1
Vehicle Speed: 50 km/hr
Vehicle Weight: 3100 kg
Polygon Area: 5.57 km²
Distance Traveled: 5 km

Distance Traveled >= 0.0

Figure 4.15. Information Required Under the Vehicle Parameters Tab

The 'Sources' tab is active, showing a list of source types with checkboxes. 'Point Sources' is checked, with sub-items 'Yakima (TEMP)' and 'Stack (TEMP)'. 'Line Sources' is unchecked. 'Area Sources' is checked, with sub-item 'Field (TEMP)'. On the right, there are four icons: a blue dot, a blue line graph, a white envelope, and a purple document. A line points from a text box to the blue dot icon.

Sources
☒ Point Sources
 ☐ Yakima (TEMP)
 ☒ Stack (TEMP)
☐ Line Sources
☒ Area Sources
 ☒ Field (TEMP)

Newly created sources in the categorized source list

Figure 4.16. Area Sources List on the Sources Tab

Parameter	Value	Unit
Wind Speed	2.2	m/s
Wind Direction	240	
Mixing Height	500	m
Ambient Temperature	25	C
Relative Humidity	50	%
Ambient Pressure	1000	mb
Atmospheric Stability	E - Slightly Stable	

Wind Direction >= 0 and Wind Direction <= 360

Buttons: Defaults, OK, Cancel

Figure 4.17. Completed Meteorological Form

4.7.8 Setting Release and Simulation Duration

The final step is to set the “Release Period” and “Simulation Scenario” details on the main DUSTRAN control panel (see Figure 4.18). The release duration is how long the sources release material, whereas the scenario duration is how long to simulate the released material. Set the Release Period’s “Start Time” for 7 a.m. (early morning release), and set the “Release Duration” for 3 hrs. For the simulation, set the “Time Zone” to PST, the “Start Date” to June 16, 2005, the “Start Time” to 4 a.m., and the “Run Duration” to 8 hrs. (*Note:* the simulation start time must begin before sunrise, as CALMET, the meteorological model in DUSTRAN, needs to calculate the hourly surface heat flux from sunrise until the end of scenario or sunset, whichever occurs first.) Lastly, verify that the “Simulation Type” is set to “Source Emissions” as the scenario involves modeling the downwind dispersion from individual source types.

After entering the proper “Release Period” and “Simulation Scenario,” click on the “Synchronize” button. Synchronization causes all the sources being simulated in DUSTRAN to have the same starting date, time, and duration. In this case, all sources will begin releasing material on June 16, 2005, at 7 a.m. PST and cease at 10 a.m. PST. The model will continue simulating the released material until 12 p.m., or until the concentration field no longer changes with time.

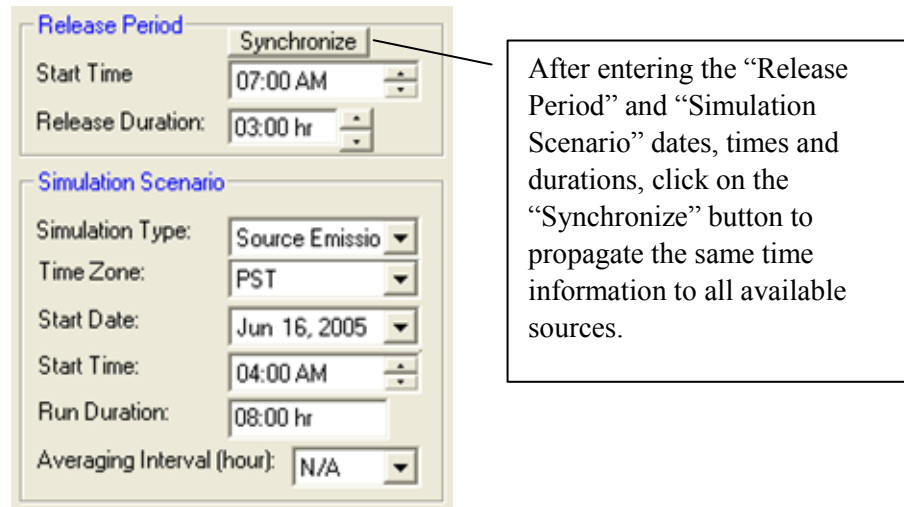


Figure 4.18. Portion of Main DUSTRAN Control Panel

4.7.9 Running DUSTRAN

After the sources, meteorology, and release-duration information have been entered, a DUSTRAN simulation can be made. To run DUSTRAN, click on the “Run Simulation” button (see Figure 4.19).

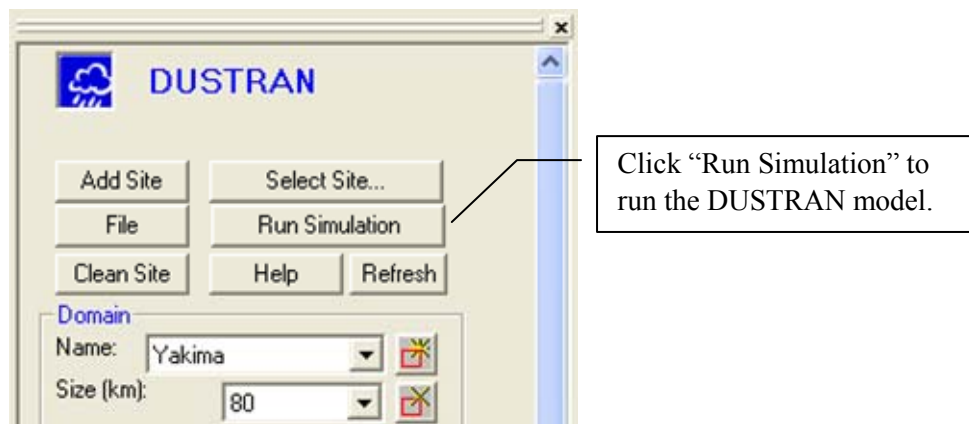


Figure 4.19. “Run Simulation” Button for Running DUSTRAN Simulation

4.7.10 Displaying Model Output

After the models finish running, click on the “Display Options” tab. Check “Contours” and “Wind Vectors” so that the plume contours and wind field will be displayed in ArcMap (see Figure 4.20). Wind vectors can be displayed for various layers throughout the domain; 20 meters is the top of the first layer, with mid-cell corresponding to 10 meters above ground level:

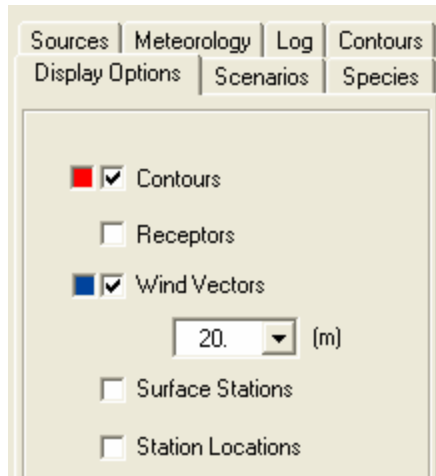


Figure 4.20. Choices After Clicking the “Display Options” Tab

4.7.11 Viewing Model Results

For each model time step, DUSTMAN calculates plume concentration and exposure as well as deposition and cumulative deposition. To view a particular contour, click on the “Contours” tab and choose from the “Contour Types” listbox (see Figure 4.21):

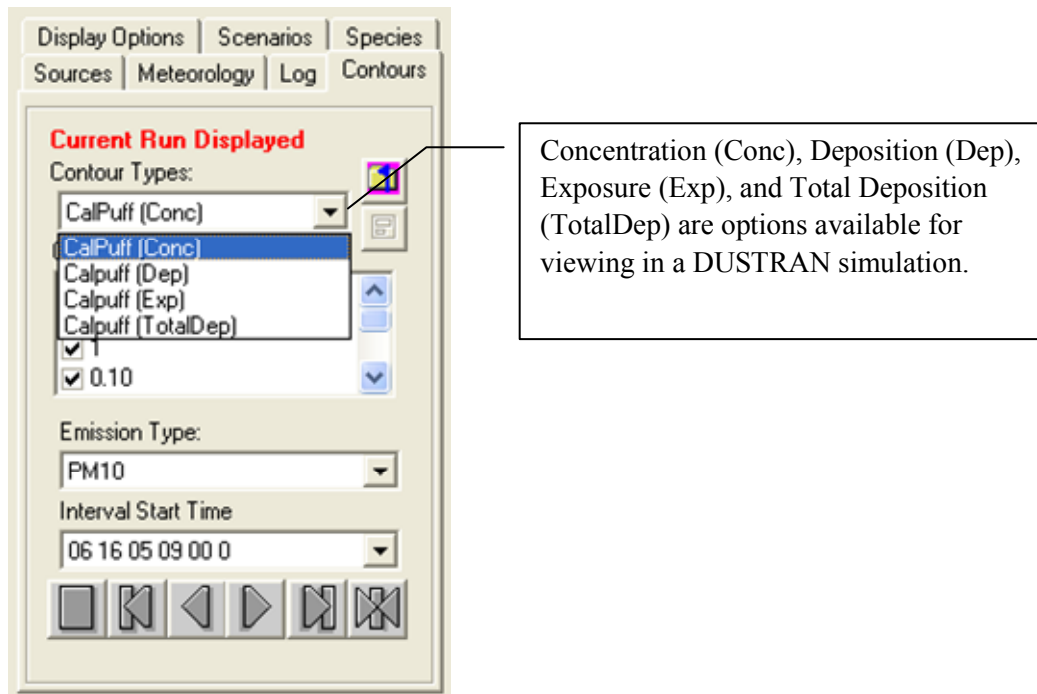


Figure 4.21. “Contour Types” Listbox

In this example, select “Conc” to display hourly concentrations within ArcMap.

For a given contour type, numerous “Contours” are available for displaying. To display a particular contour interval, check the box next to the contour value. The default selection is normally adequate for displaying the maximum extent of the plume envelope.

To view a particular time step, select an interval from the “Interval Start Time” listbox. In this example, hourly time steps are available from the start of the release (7:00 a.m. local time) till the end of the run duration. Choose the 9:00 a.m. time step, which corresponds to the 1-hour (9:00 a.m. till 10:00 a.m.) average concentration (see Figure 4.22):

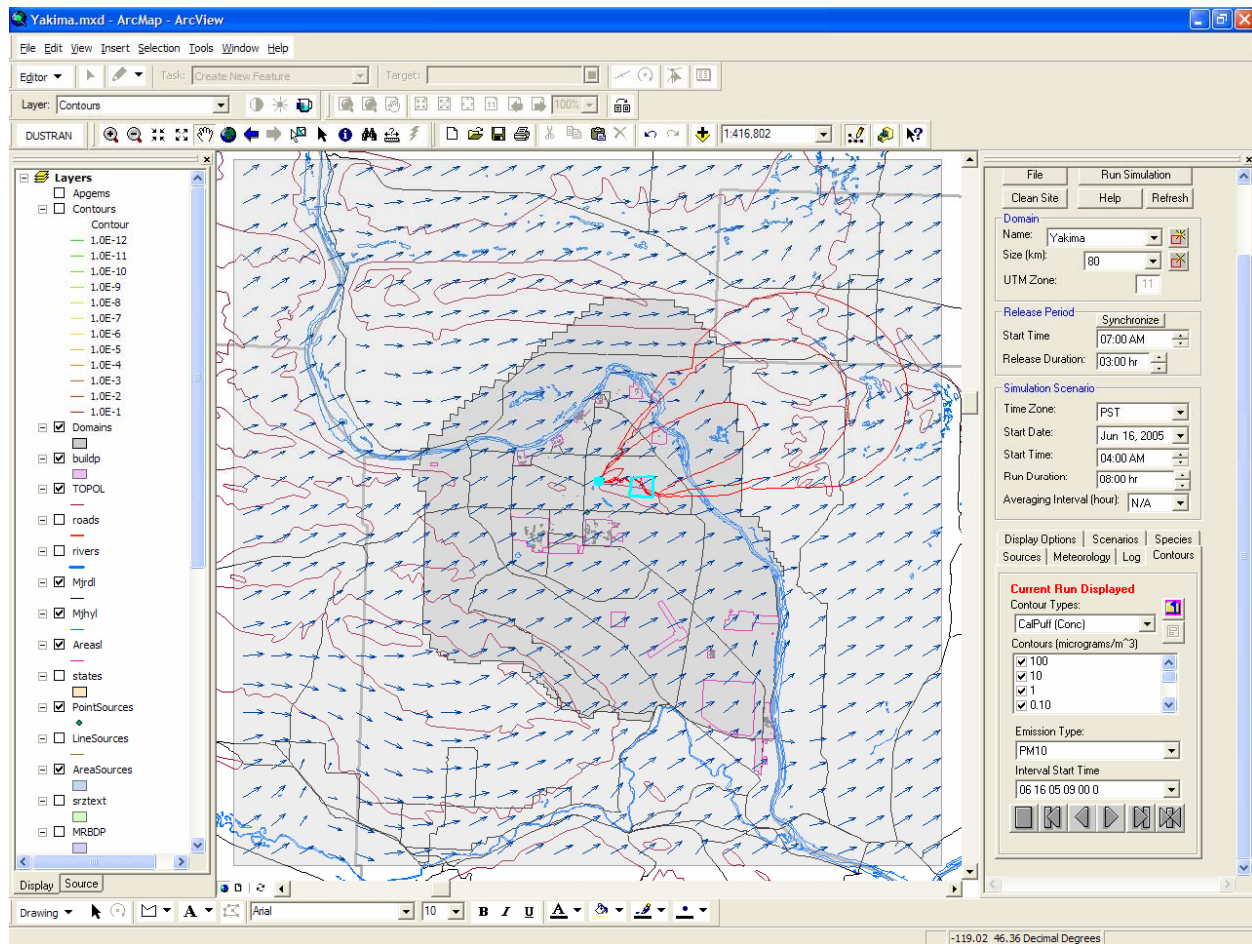


Figure 4.22. Display of Concentration Contours and Wind Vectors for the Hour from 9 to 10 a.m.

Notice in the above image that the two plumes (point and area-source plumes) have merged. In addition, note the distortion to the wind field due to the local topography. The distortion is caused by terrain blocking because of the early-morning stability and slope flow due to cold-air drainage.

4.8 Comparison with Field Data

The field data needed to validate the vehicle-generated PM₁₀ source model of DUSTRAN are meteorological quantities (e.g., winds), PM₁₀ air concentrations, and location and timing of all vehicle activity during a military training exercise. The only field data set sufficient for validation of the DUSTRAN vehicle-generated PM₁₀ source model is that collected during training exercises at the NTC at Fort Irwin, California. The data were collected by PNNL for FORSCOM. A sufficient number of PM₁₀ measurements were made surrounding the vehicle activity areas such that impacts of the training activities were distinguishable from ambient PM₁₀ concentrations. Additionally, sufficient details on the activities of all vehicles in the training exercises were available to specify the vehicle activities within DUSTRAN. The comparison of DUSTRAN simulations with the Fort Irwin field data is given next.

On July 14, 2001, a forces move-out operation took place from 0500 to 1500 PST where two Tactical Forces (TF1 and TF2) and one Operational Force (OPFOR) moved from the cantonment area at Fort Irwin to their respective staging areas. During the 10-hour period of the move-out operation, nearly 750 vehicle trips were made to their respective three staging areas as shown in Figure 4.23. The cantonment area is located at the intersection of the red lines in the figure; OPFOR moved initially to the west, TF1 moved to the northeast, and TF2 moved to the southeast. Table 4.6 gives the number of trips by vehicle type for each of the three forces and the distance traveled for each trip.

Table 4.6. NTC Forces Move-out on July 14, 2001

FORCE	Distance (km)	HET^(a)	Humvee	5-Ton Truck
OPFOR	67	298	24	33
TF1	13	96	50	50
TF2	23	96	50	50

(a) Heavy Equipment Transport.

DUSTRAN does not track each vehicle as it travels along the roadway because vehicle locations as a function of time are not typically known. The model estimates the total dust generated from all vehicle activity along each road and assumes that the dust enters the modeling domain uniformly along the road and uniformly in time during the duration of the activity. DUSTRAN was run for the 24-hour period of July 14, 2001, and 24-hour-average near-surface PM₁₀ concentrations were calculated. The meteorological data from the U.S. Air Force NTC meteorological network were used in the simulation. Figure 4.23 shows the 0500- to 0600-hour-average PM₁₀ concentration isopleths and the nine PM₁₀ measurement locations. Figure 4.24 shows the time variation of the DUSTRAN ground-level PM₁₀ concentrations through the duration of the move-out activity.

The 24-hour-average PM₁₀ concentrations from DUSTRAN compared favorably with the concentrations at the seven downwind sampling locations (Table 4.7). The modeled concentrations in Table 4.7 are from the grid point nearest the measurement location. Also shown in the table are the modeled maximum concentrations within 4 kilometers (two model grid cell) of the measurement location, showing that the DUSTRAN results compared even

better with the observations if an exact point-to-point comparison is somewhat relaxed. Note that the measured PM_{10} concentrations were adjusted by subtracting the measured upwind concentration of $12 \mu\text{g}/\text{m}^3$ from the downwind observations. This was necessary because this simulation of DUSTSTRAN was not based on a complete PM_{10} emission inventory for the entire region.

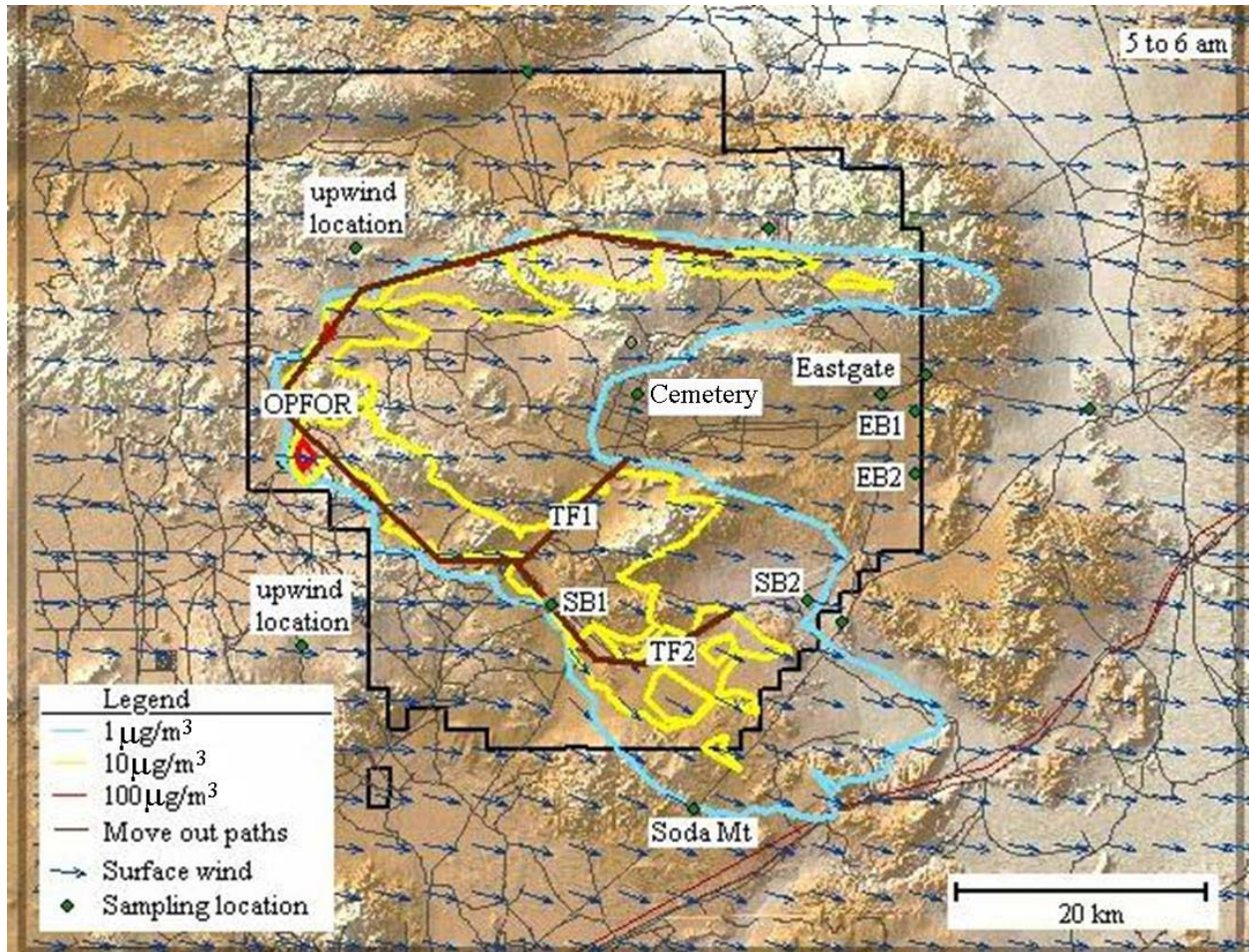


Figure 4.23. Hour-Average Modeled PM_{10} Concentrations One Hour After Beginning of Training Move-Out Operations at NTC on July 14, 2001. The nine measurement locations and the three move-out paths (OPFOR, TF1, and TF2) are shown.

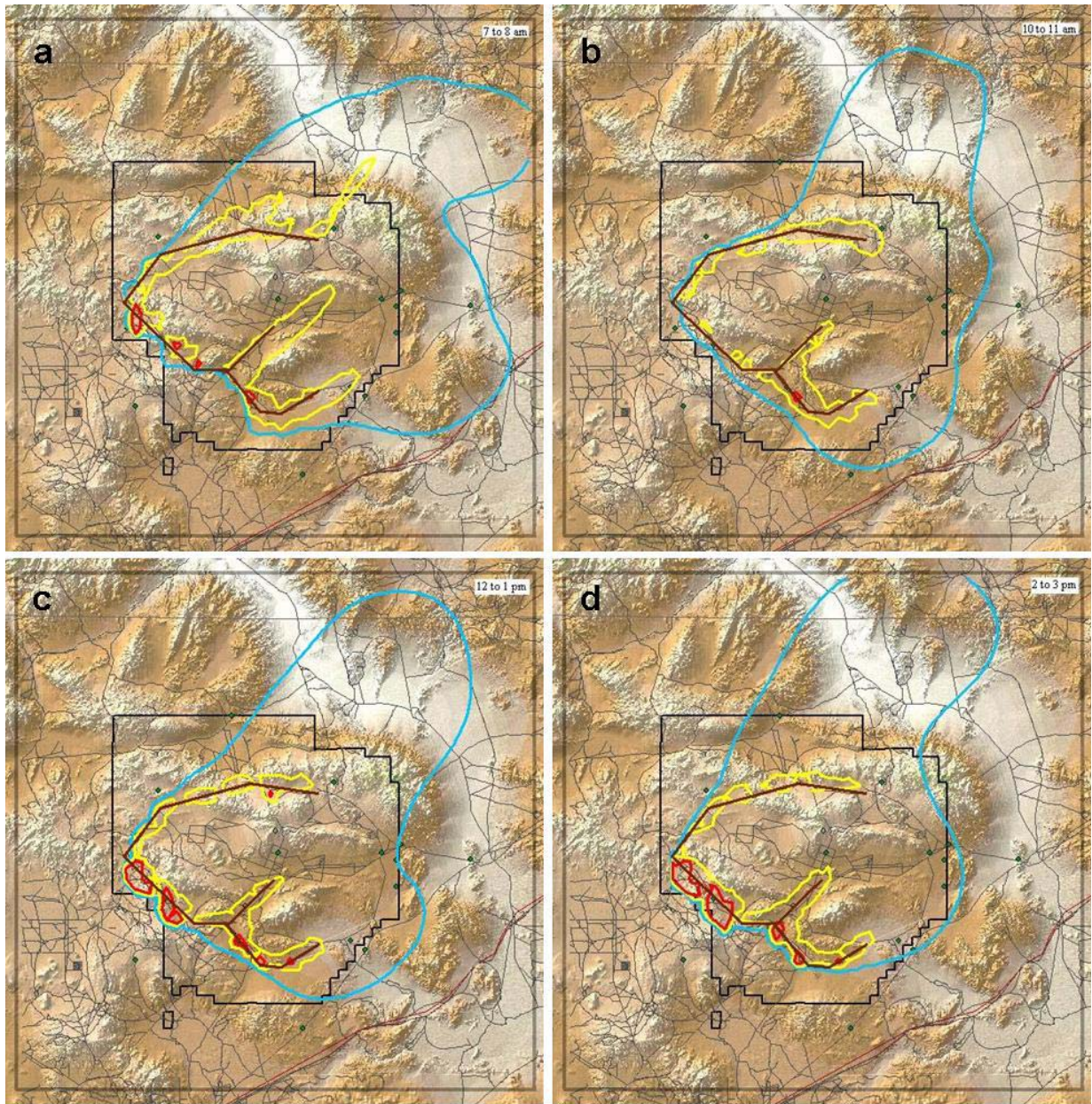


Figure 4.24. Hour-Average Modeled PM₁₀ Concentrations for Training Move-Out Operations at NTC on July 14, 2001. The concentration isopleths are 1 (blue), 10 (yellow), and 100 (red) µg/m³. The times shown are ending hour 0800 (a), 1100 (b), 1300 (c) and 1500 PST (d).

Table 4.7. Comparison of Modeled and Observed 24-Hour-Average PM₁₀ Concentrations (µg/m³) at NTC

Measurement Location	Observed ^(a)	Modeled	Modeled (within 4 km)
Soda Mt	1	1	1
Eastgate	3	1	1
EB2	3	1	2
Cemetery	4	3	4
EB1	5	1	2
SB2	10	3	10
SB1	105	90	150
(a) Minus upwind concentration of 12 µg/m ³ .			

The field data needed to validate the wind-generated PM₁₀ source model of DUSTRAN are meteorological quantities (e.g., winds), PM₁₀ air concentrations, and surface characteristics (i.e., soil texture and vegetation cover) of the dust-source region. The data selected to evaluate this DUSTRAN component were collected independently in response to a large range fire that occurred on the DOE's Hanford Site in Eastern Washington State. Known as the "24 Command Wildland Fire," it began on June 27, 2000. The fire was caused by a highway accident on the western edge of the Hanford Site (DOE 2000) and burned nearly 700 km² over a 6-day period. Most of the fire occurred on the Fitzner-Eberhardt Arid Lands Ecology Reserve, a shrub-steppe habitat on the Hanford Site that had been set aside for preservation (Neitzel 2005). On many portions of the burn area, vegetation was completely destroyed, leaving only ash and charred remains.

Particulate-matter mass concentrations in air began to be monitored on the Hanford Site during February 2001. Mass concentration of PM₁₀ was measured at the Hanford Meteorological Station using a tapered element oscillating microbalance (TEOM), an EPA-approved, equivalent-method instrument. This instrument measures the difference in mass collected on a filter by measuring the change in frequency of oscillation of the filter and has been used by many researchers to measure PM₁₀ concentrations resulting from windblown dust (e.g., Claiborn et al. 2000; Sundram et al. 2004). The TEOM was set to record hourly averages of PM₁₀ concentrations. Based on calibrations and quality-control checks, total errors in the measured PM₁₀ concentrations are expected to be less than 10%.

Meteorological inputs for DUSTRAN were obtained from the Hanford Meteorological Station and the network of 30 meteorological towers maintained on and around the Hanford Site. These consist primarily of 9-m towers with wind speed and direction, temperature, humidity, and pressure measured continuously and recorded on a 15-minute interval (Hoitink et al. 2004). Included in the network are three 61-m towers and one 120-m tower. This meteorological network was used as the input to the CALMET model to create the wind field used by CALGRID, with the taller towers providing the required upper-air data.

Soil-texture inputs to DUSTRAN were based on a detailed Hanford soil classification data set (Hajek 1966) and a map of Washington State soil types maintained by Washington State University (Boling et al. 1998). Vegetation coverage inputs for the fire footprint were based on

measurements made after the fire by the Nature Conservancy (Evans and Lih 2005) and Pacific Northwest National Laboratory (Poston et al. 2006). Elsewhere in the modeling domain, the vegetation mask was set according to the Olson World Ecosystem database. Ecosystem categories in the domain were 40 (cool grass/shrub, snowy in most years), largely east and south of the TEOM sampling location, and 52 (cool/cold shrub semidesert/steppe) to the north and west. These categories have mask values of 0 and 0.5, respectively.

Figure 4.25 shows time series of measured and modeled PM_{10} concentrations for a simulation of March 13, 2001. Observed dust concentrations were very low until about 0900 local standard time (LST). At that time, winds (not shown) began to increase, reaching an average speed of about 15 m s^{-1} by 1300 LST. The wind direction was initially from the west but became southwesterly with the onset of the stronger wind. This high wind speed then persisted until about 1700 LST. Corresponding to the increased wind speed, both the modeled and observed dust concentrations rose dramatically. The largest modeled dust concentrations were close to those observed until 1600 LST when rain was reported. Since soil moisture information was not available for this simulation, the model was being run in a “dry” mode. It was therefore insensitive to the rainfall and continued to simulate high dust concentrations in the strong winds that persisted in the early part of the rain event.

Under separate funding support, the preliminary simulation described above is being refined to use information on more finely resolved vegetation cover for both the fire footprint and the surrounding region. A paper comparing DUSTRAN results with field data from multiple days using these more finely resolved input files is being prepared for submission to a scientific journal. However, even the preliminary results indicate that DUSTRAN is an accessible and effective tool for simulating dust events due to wind erosion. Given the large uncertainties that currently exist both in the measurements of individual processes that contribute to vertical dust flux and in the parameterizations of these processes, it seems unlikely that a more complicated wind-erosion model would be significantly more successful in estimating concentrations of wind-blown dust.

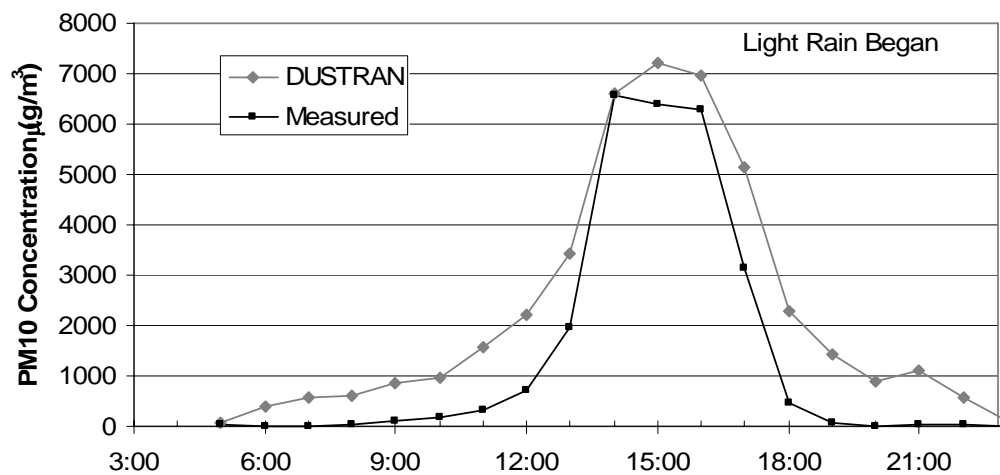


Figure 4.25. Comparison of Measured (TEOM) and DUSTRAN-Modeled PM₁₀ Concentrations from Windblown Dust as a Function of Time at the Hanford Meteorological Station on March 13, 2001

5.0 Conclusions

In this report we have described the DUST TRANsport, or DUSTRAN, modeling system. DUSTRAN is a comprehensive dispersion modeling system, consisting of a dust-emissions model, a diagnostic meteorological model, and dispersion models that are integrated seamlessly into ESRI's ArcMap GIS. DUSTRAN functions as a console application within ArcMap and allows the user to interactively create a dust-release scenario and run the underlying models. Through the process of data layering, the model domain, sources, and results—including the calculated wind-vector field and plume contours—can be displayed with other spatial and geophysical data sources to aid in analyzing and interpreting the scenario. DUSTRAN can be used to estimate the impacts of military operations on particulate air quality (both National Ambient Air Quality Standards and Federal Class I area impacts). The air-quality models in DUSTRAN incorporate the affects of complex terrain (e.g., enhanced diffusion, flow blocking and channeling, slope flows) on dispersion, and the GIS in DUSTRAN is a widely used system familiar to many military and civilian personnel.

The DUSTRAN atmospheric dust-dispersion modeling system runs on a personal computer under the Microsoft Windows XP operating system. DUSTRAN is fully documented with the technical foundations and user's instructions given by Allwine et al. (2006b). DUSTRAN and its required setup files are available on installation CDs from PNNL. Users need to have ESRI's ArcMap GIS (Version 9) installed on their computers to operate DUSTRAN.

DUSTRAN is constructed from widely used, scientifically defensible atmospheric models and model components. The modeling system efficiently couples these modeling components and advances the state-of-science in dust-emission formulations. DUSTRAN is based on ESRI's ArcMap GIS, the EPA-approved CALPUFF dispersion model, and the widely used CALGRID dispersion model. The CALMET model provides the meteorological fields for the CALPUFF and CALGRID dispersion models. DUSTRAN includes dust-emission models for estimating emissions from both wheeled-military-vehicle activities and dust generated by wind erosion.

The wheeled-vehicle PM_{10} emission factors from SERDP project SI-1191 and the dust-emission factors from EPA's AP-42 document for wheeled vehicles operating on paved and unpaved roads form the basis of the current vehicle-generated dust-emission model in DUSTRAN. Current SERDP projects SI-1399 and SI-1400 will provide dust-emission factors over the next few years from field studies investigating unique military dust-generating sources, such as tracked vehicles, fixed-wing and rotary-wing aircraft, and artillery back-blast. These new emission factors will be incorporated into DUSTRAN within the SI-1399 project as they become available.

The wind-generated dust-emission model in DUSTRAN is based on formulations from the current scientific literature. These formulations relate wind characteristics, soil-texture categories, and vegetation-cover categories to dust flux (mass per unit area per unit time) into the atmosphere. DUSTRAN includes files of soil-texture categories and vegetation-cover categories covering the contiguous United States for use in estimating dust emissions from wind erosion. If finer resolution files of soil texture and vegetation cover are available for a specific area, DUSTRAN allows these finer resolution files to be used.

Since the CALPUFF atmospheric dispersion model in DUSTRAN is an EPA-recommended model, the dispersion (transport and diffusion) components of the model have already been validated against tracer data. Limited field data are available for validating DUSTRAN for proper simulation of dust emissions from military-vehicle activities on unpaved roads and in off-road training areas. DUSTRAN compared favorably with PM₁₀ concentrations measured at several locations during a day of move-out operations at Fort Irwin, California. DUSTRAN also compared favorably with windblown-dust measurements for dust generated at the Hanford site. The results of the wind-generated-dust simulations are currently being prepared for submission to a scientific journal.

6.0 Transition Plan

The first step in transitioning DUSTRAN for operational use at military training ranges has been completed by making the DUSTRAN modeling system's User's Guide (Allwine et al. 2006b) and installation CDs available from PNNL. Internet downloads via the PNNL public ftp site are possible, and we are investigating making a limited version of DUSTRAN available directly on the Internet. Additionally, encouraging widespread use of the DUSTRAN modeling system through an effective transition plan is essential for maximizing the benefit of DUSTRAN in addressing PM air-quality issues at military facilities.

DUSTRAN has recently been applied at the Fort Bliss, Texas, military training range. At the request of the Fort Bliss air programs manager, DUSTRAN was successfully used to estimate the impacts of Fort Bliss move-out and combat training activities on PM₁₀ air quality in the vicinity of Fort Bliss. Two technical reports (Chapman et al. 2006a and 2006b) giving the DUSTRAN results for Fort Bliss were provided to the air-programs manager, and DUSTRAN is currently being installed at Fort Bliss for use by the air-programs manager.

A reasonable approach for effectively transitioning DUSTRAN for broad application at military ranges is through a multi-year transition project (possibly through the Environmental Security Technology Certification Program) implementing the use of DUSTRAN at two-to-three military installations at various locations in the United States. The project will allow appropriate military staff to be trained in the use of DUSTRAN and will permit application of DUSTRAN to installation-specific air-quality issues. Implementation at multiple military installations will facilitate the DUSTRAN user interface being made more "friendly" by ongoing interaction between the users and DUSTRAN developers. It also will identify clearly those features of DUSTRAN that are most important to military users, thus allowing proper prioritization of potential DUSTRAN extensions and enhancements. A multi-year transition project will facilitate finding an organization willing and capable of long-term support of the DUSTRAN system for providing technical consulting, software maintenance, and periodic upgrades as operating systems change and technical advances are made.

The following elements are required to make sure that the long-term application of DUSTRAN addresses military PM air-quality issues: 1) scientific and regulatory acceptance, 2) software availability and distribution, 3) outreach to potential users, 4) technical support and consulting, 5) software maintenance and updates, and 6) improvements based on user feedback, scientific advances, and future applications. The above six elements will need to be operational to conclude the most effective transition project for making sure that DUSTRAN will be used long term.

Certain progress was made by PNNL within SI-1195 in advancing some of the above six elements of the "DUSTRAN Operational Program" (DUSTOP). Specifically, presentations at scientific meetings by project staff have served to increase scientific acceptance of DUSTRAN while also involving outreach to potential users. Efforts to prepare open-literature manuscripts, both on the wind-blown dust module and on the overall DUSTRAN modeling system, were begun and are expected to further advance scientific acceptance. In combination with funding from the Ft. Bliss air-programs manager, an initial process for distributing software was

developed, and a program reflecting initial technical support and training requirements was designed. Initial modifications and improvements to the DUSTRAN modeling system have been made through the ongoing SI-1399 project. However, adequately fostering implementation and use of DUSTRAN and providing necessary technical support and timely updates will involve additional, ongoing financial support.

Next is summarized the current status of the six DUSTOP elements resulting from the efforts in SI-1195. This information will be useful in planning and scoping a DUSTRAN transition project that will be necessary for advancing the use of DUSTRAN for addressing PM air-quality issues.

Scientific and Regulatory Acceptance—The DUSTRAN primary dispersion model is CALPUFF, which is an EPA “recommended” model that has previously been validated against tracer data. The dust-emission factors in DUSTRAN have current regulatory acceptance (AP-42 vehicle-emission factors), have been published in the scientific literature (DRI vehicle emission factors), or are based on formulations in the scientific literature (wind-generated dust). Additionally, within SI-1195 efforts, DUSTRAN compared favorably with windblown dust measurements at the Hanford site. These results are currently being prepared for submission to a scientific journal to validate the wind-generated dust formulation in DUSTRAN. In another SI-1195 effort, DUSTRAN results compared favorably with PM₁₀ concentrations measured at several locations during a day of move-out operations at Fort Irwin, California. The numbers and types of vehicles in the move-out were known in addition to the time of the move-out operations. These vehicle data in addition to the meteorological data were supplied to DUSTRAN, producing the favorable comparison with the measured PM₁₀ concentrations.

The steps remaining to have regulatory acceptance of DUSTRAN for addressing PM air-quality issues from fugitive dust sources are to 1) complete the publication of a journal article on the results of the wind-generated dust estimates compared with field data, 2) prepare and publish a journal article documenting the DUSTRAN system and compare it with field measurements of PM₁₀ concentrations resulting from significant vehicle activity (the comparison with Fort Irwin data may be sufficient), and 3) use DUSTRAN in some air-quality assessments to establish its acceptance with the regulatory community. This was recently done at Fort Bliss where DUSTRAN results are potentially being used in an Environmental Assessment.

Software Availability and Distribution—DUSTRAN software and documentation is currently available by request from PNNL.

Outreach to Potential Users—With the recent completion and release of DUSTRAN 1.0, minimal outreach to potential users has occurred. A poster and demonstration of DUSTRAN was presented at the 2006 SERDP/ESTCP^(a) Partners in Environmental Technology Symposium & Workshop. Additionally, the DUSTRAN User’s Guide is available on the PNNL external website for general access. A project for the Fort Bliss air-programs manager, Jesse Moncada, was recently completed. Mr. Moncada understands the utility of DUSTRAN for addressing PM air-quality issues and may pass the information along to interested parties at other military installations.

(a) ESTCP = Environmental Security Technology Certification Program.

Technical Support and Consulting—Currently, there is no funding available for technical support and consulting for DUSTRAN users.

Software Maintenance and Updates—Currently, there is no funding for software maintenance and updates. A limited amount of DUSTRAN software maintenance can be accommodated on the existing SI-1399 project to address minor updates to computer operating systems and ArcMap.

Modeling System Improvements—The ongoing SI-1399 project includes improvements to DUSTRAN for treating PM emissions from unique military vehicles, such as tracked vehicles, fixed-wing aircraft, rotary-wing aircraft, and artillery back-blast.

To maintain an updated and state-of-the-art modeling system, DUSTRAN should have an ongoing improvement plan. For example, DUSTRAN has the capability and flexibility for range staff to track in near-real-time the impacts of training activities on PM air concentrations. Currently, the CALPUFF model in DUSTRAN operates on 1-hour time steps. However a “sub-hourly” version of CALPUFF has recently been made available by the CALPUFF developers. DUSTRAN should be updated to use the sub-hourly version of CALPUFF when possible. Of course, having a “sub-hourly” CALPUFF does not mean that DUSTRAN can necessarily operate at sub-hourly time steps. That depends on the meteorological data also being available at sub-hourly intervals. DUSTRAN can also be used as an emergency-response system at military facilities. Having DUSTRAN able to operate at sub-hourly intervals will allow DUSTRAN to be a more viable emergency response system.

Another advance that may make DUSTRAN a more useful tool for addressing atmospheric dispersion issues at military facilities is to convert it to a web-based application. A web-based DUSTRAN system would potentially allow users to more easily use DUSTRAN. Additionally, each user would not need to install the GIS or DUSTRAN software. Software upgrades and maintenance would be simpler. Significant effort would be needed to create a web-based version of DUSTRAN, and long-term support would be required for technical support and software maintenance system upgrades.

7.0 References

Allwine KJ, FC Rutz, WJ Shaw, BG Fritz, and BL Hoopes. 2004. *Third Annual Progress Report: Development of a GIS-Based Complex Terrain Model for Atmospheric Dust Dispersion*. PNNL-14555, Pacific Northwest National Laboratory, Richland, WA.

Allwine KJ, FC Rutz, JP Rishel, JG Droppo, SL Bird, and H Thistle. 2006a. *SPRAYTRAN 1.0 User's Guide: A GIS-Based Atmospheric Spray Droplet Dispersion Modeling System*. PNNL-16075, Pacific Northwest National Laboratory, Richland, WA.

Allwine KJ, FC Rutz, WJ Shaw, JP Rishel, BG Fritz, EG Chapman, BL Hoopes and TE Seiple. 2006b. *DUSTRAN 1.0 User's Guide: A GIS-Based Atmospheric Dust Dispersion Modeling System*. PNNL-16055, Pacific Northwest National Laboratory, Richland, WA.

Boling M, B Frasier, and A Busacca. 1998. *General Soil Map of Washington*. Department of Crop and Soil Sciences, Washington State University, Pullman, Washington. Available at <http://remotesens.css.wsu.edu/washingtonsoil/index.htm> (accessed 05-06-2007).

Chapman EG, JP Rishel, FC Rutz, TE Seiple, RK Newsom, and KJ Allwine. 2006a. *Dust Plume Modeling at Fort Bliss: Full Training Scenario*. PNNL-15935, Pacific Northwest National Laboratory, Richland, WA.

Chapman EG, JP Rishel, FC Rutz, TE Seiple, RK Newsom, and KJ Allwine. 2006b. *Dust Plume Modeling at Fort Bliss: Move-Out Operations, Combat Training and Wind Erosion*. PNNL-16123, Pacific Northwest National Laboratory, Richland, WA.

Claiborn CS, D Finn, TV Larson, and JQ Koenig. 2000. "Windblown dust contributions to high PM_{2.5} concentrations." *J. Air and Waste Man. Assoc.* 50:1440-1455.

DOE (see U.S. Department of Energy)

EPA (see U.S. Environmental Protection Agency)

Evans JR, and MP Lih. 2005. *Recovery and Rehabilitation of Vegetation on the Fitzner-Eberhardt Arid Lands Ecology Reserve, Hanford Reach National Monument, Following the 24 Command Fire*. Prepared by the Nature Conservancy of Washington for the U.S. Fish and Wildlife Service. Available at <http://www.fws.gov/hanfordreach/documents/ale-report.pdf> (accessed 05-06-2007).

Fecan F, B Marticorena, and G Bergametti. 1999. "Parameterization of the increase of the Aeolian erosion threshold wind friction velocity due to soil moisture for arid and semi-arid areas." *Annales Geophys.* 17:194-157.

Geernaert GL. 1990. "Bulk parameterizations for the wind stress and heat fluxes." In: *Surface Waves and Fluxes, Vol. 1*, edited by GL Geernaert and WJ Plant, Kluwer Academy, Norwell, MA.

- Gifford FA, Jr. 1976. "Turbulent diffusion—typing schemes: a review." *Nucl. Saf.* 17:68-86.
- Gillette DA, and R Passi. 1988. "Modeling dust emission caused by wind erosion." *J. Geophys. Res.* 93:14233-14242.
- Gillies JA. 2006. "CP-1399 Fact Sheet: Particulate Matter Emissions Factors for Dust from Unique Military Activities." Strategic Environmental Research and Development Program, Arlington, VA. Available at: http://www.serdp.org/research/upload/CP_1399.pdf, (accessed 05-06-2007).
- Gillies JA, V Etyemezian, H Kuhns, D Nikolic, and DA Gillette. 2005a. "Effect of vehicle characteristics on unpaved road dust emissions." *Atmos. Environ.* 39:2341-2347.
- Gillies JA, WP Arnott, V Etyemezian, H Kuhns, H Moosmuller, D DuBois, M Abu-Allaban, G Schwemmer, DA Gillette, WG Nickling, R Varma, T Wilkerson, and R Varma. 2005b. *Characterizing and Quantifying Local and Regional Particulate Matter Emissions from Department of Defense Installations*. Final report for Project SI (formerly CP)-1191, Strategic Environmental Research and Development Program, Arlington, VA. Available at <http://docs.serdp-estcp.org/viewfile.cfm?Doc=CP%5F1191%5FFR%2Epdf>, (accessed 05-06-2007).
- Grini A., and C.S. Zender. 2004. "Roles of saltation, sandblasting, and wind speed variability on mineral dust aerosol size distribution during the Puerto Rican Dust Experiment (PRIDE)." *Journal of Geophysical Research*. 109: D07202.
- Hajek BF. 1966. *Soil Survey Hanford Project in Benton County Washington*. BNWL-243, Battelle Northwest Laboratory, Richland, WA.
- Hoitink DJ, KW Burk, JV Ramsdell, and WJ Shaw. 2004. *Hanford Site Climatological Data Summary 2003 with Historical Data*. PNNL-14616, Pacific Northwest National Laboratory, Richland, WA. Available at <http://www.pnl.gov/main/publications> (accessed 05-06-2007).
- Irwin JS. 1998. *Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts*. EPA-454/R-98-019, Office of Air Quality Planning and Standards, Research Triangle Park, NC.
- Kim BJ. 2006. "CP-1400 Fact Sheet: Development of Emission Factors for Dust Generated by Unique Military Activities." Strategic Environmental Research and Development Program, Arlington, VA. Available at: http://www.serdp.org/research/upload/CP_1400.pdf, (accessed 05-06-2007).
- Kirkham RR, MA Chamness, CJ Driver, and BC Barfuss. 2005. *Air Quality and Road Emission Results for Fort Stewart, Georgia*. PNNL-14933, Pacific Northwest National Laboratory, Richland, WA. Available at: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14933.pdf, (accessed 05-06-2007).

Neitzel DA (editor). 2005. *Hanford Site National Environmental Policy Act (NEPA) Characterization*. PNNL-6415, Rev. 17, Pacific Northwest National Laboratory, Richland, WA. Available at <http://www.pnl.gov/main/publications> (accessed 05-06-2007).

Nickovic S, G Kallos, A Papadopoulos, and O Kakaliagou. 2001. "A model for prediction of desert dust cycle in the atmosphere." *J. Geophys. Res.* 106:18113-18129.

Office of the Federal Coordinator for Meteorology (OFCM). 1999. *Directory of Atmospheric Transport and Diffusion Consequence Assessment Models*. FCM-I3-1999, Silver Spring, MD.

Olson JS. 1992. "World Ecosystems (WE1.4). Digital Raster Data on a 10-minute Cartesian Orthonormal Geodetic 1080×2160 grid." In: *Global Ecosystems Database, Version 2.0*. Boulder, CO. Available at: http://www.ngdc.noaa.gov/seg/cdroms/ged_iiia/datasets/a05/ow.htm (accessed 05-06-2006).

Pasquill F. 1976. *Atmospheric Dispersion Parameters in Gaussian Plume Models: Part II. Possible Requirements for Change in the Turner Workbook Values*. EPA-600/4-76-030b, U.S. Environmental Protection Agency, Research Triangle Park, NC.

Poston TM, RW Hanf, RL Dirkes, and LF Morasch. 2006. *Hanford Site Environmental Report for Calendar Year 2005*. PNNL-15892, Pacific Northwest National Laboratory, Richland, WA. Available at: <http://www.pnl.gov/main/publications> (accessed 05-06-2007).

Scire JS, DG Strimaitis, and RJ Yamartino. 2000a. *A User's Guide for the CALPUFF Dispersion Model (Version 5)*. Earth Tech, Inc., Concord, MA.

Scire JS, FR Robe, ME Fernau, and RJ Yamartino. 2000b. *A User's Guide for the CALMET Meteorological Model (Version 5)*. Earth Tech, Inc., Concord, MA.

Scire JS, RJ Yamartino, GR Carmichael, and YS Chang. 1989. *CALGRID: A Mesoscale Photochemical Grid Model Volume II – User's Guide*. California Resources Board, Sacramento, CA.

Shao Y. 2000. *Physics and Modeling of Wind Erosion*. Kluwer Academic Publishers, Boston, PA.

Staub B, and C Rosenzweig. 1992. "Global Zobler Soil Type, Soil Texture, Surface Slope, and Other Properties. Digital Raster Data on a 1-degree Geographic (lat/long) 180×360 grid." In: *Global Ecosystems Database Version 2.0*. Boulder, CO, NOAA National Geophysical Data Center. Available at: http://www.ngdc.noaa.gov/seg/cdroms/ged_iiia/datasets/a11/sr.htm (accessed 05-06-2007).

Sundram I, CS Claiborn, T Strand, B Lamb, D Chandler, and K Saxton. 2004. "Numerical modeling of windblown dust in the Pacific Northwest with improved meteorology and dust emission models." *J. of Geophys. Res.* 109: D24208.

Tegen I, and I Fung. 1994. "Modeling of mineral dust in the atmosphere: sources, transport, and optical thickness." *J. Geophys. Res.* 99:22987-22914.

Turner DB. 1994. *Workbook of Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling*. Second Edition. ISBN 1-56670-023-X. CRC Press, Inc. Boca Raton, FL.

U.S. Department of Energy (DOE). 2000. *U.S. Department of Energy Response to the 24 Command Wildland Fire on the Hanford Site- June 27-July 1, 2000*. DOE/RL-2000-63, U.S. Department of Energy, Richland Operations Office, Richland, WA. Available at: <http://www.hanford.gov/docs/rl-2000-63/> (accessed 05-06-2007).

U.S. Environmental Protection Agency (EPA). 2005. "Compilation of Air Pollutant Emission Factors (AP-42)." Fifth Edition, Volume 1: *Stationary Point and Area Sources*. Research Triangle Park, NC. Available at <http://www.epa.gov/ttn/chief/ap42/> (accessed 05-06-2007).

U.S. Environmental Protection Agency (EPA). 1998. "A Comparison of CALPUFF Modeling Results to Two Tracer Field Experiments." EPA-454/R-98-009. Research Triangle Park, NC. Available at: <http://www.epa.gov/scram001/7thconf/calpuff/tracer.pdf> (accessed 05-06-2007).

Appendix A

List of Technical Publications

Appendix A: List of Technical Publications

A.1 Journal Publications

Crandall DW, and FC Rutz. 2004. “Development of a Geographic Information System-Based Dust Dispersion Modeling System for Use in the Planning and Implementation of Military Training Exercises.” *Journal of Undergraduate Research* 4:48-52.

A.2 Technical Reports

Allwine KJ, FC Rutz, WJ Shaw, JP Rishel, BG Fritz, EG Chapman, BL Hoopes, and TE Seiple. 2006. *DUSTRAN 1.0 User's Guide: A GIS-Based Atmospheric Dust Dispersion Modeling System*. PNNL-16055, Pacific Northwest National Laboratory, Richland, WA.

Allwine KJ, FC Rutz, WJ Shaw, BG Fritz, and BL Hoopes. 2004. *Third Annual Progress Report: Development of a GIS-Based Complex Terrain Model for Atmospheric Dust Dispersion*. PNNL-14555, Pacific Northwest National Laboratory, Richland, WA.

A.3 Conference Proceedings

Allwine KJ, FC Rutz, WJ Shaw, JP Rishel, BG Fritz, EG Chapman, TE Seiple, and BL Hoopes. 2006. “DUSTRAN: A GIS-Based Atmospheric Dust Dispersion Modeling System.” Paper presented at the *10th Annual George Mason University Conference on Atmospheric Transport and Dispersion Modeling*, Fairfax, VA, on August 3, 2006.

Rutz FC, BL Hoopes, DW Crandall, and KJ Allwine. 2004. “Development of a GIS Based Dust Dispersion Modeling System.” In: Proceedings of the *ESRI International User Conference*, Environmental Systems Research Institute Inc., San Diego, CA.

Allwine KJ, FC Rutz, and CJ Driver. 2002. “Demonstration of a Prototype GIS-Based Dust Dispersion Modeling System.” In: Proceedings of the *Real World Clean Air Symposium*. U.S. Army Forces Command, National Training Center, and Fort Irwin. May 21-23, 2002, San Diego, CA.

Allwine KJ, FC Rutz, and CJ Driver. 2001. “In Progress Review – Development of a GIS-Based Dust Dispersion Model.” In: Proceedings of the *Real World Clean Air Symposium*. U.S. Army Forces Command, National Training Center, and Fort Irwin. April 24-26, 2001, San Diego, CA.

A.4 Published Abstracts

Allwine KJ, JR, FC Rutz, JP Rishel, WJ Shaw, EG Chapman, TE Seiple, RK Newsom, and JD Moncada. 2006. “DUSTRAN: A GIS-Based Dispersion Model for Assessing Atmospheric Transport of Dust Emissions.” Poster for presentation at the *Annual SERDP/ESTCP-sponsored*

Partners in Environmental Technology Technical Symposium & Workshop, November 28-30, 2006, Washington, DC.

Allwine KJ, F Rutz, B Hoopes, W Shaw, and B Fritz. 2003. "Atmospheric Dust Dispersion Modeling System." Poster presented at the *Annual SERDP/ESTCP Partners in Environmental Technology Technical Symposium and Workshop*, December 2-4, 2003, Washington, DC.

Allwine KJ, F Rutz, B Hoopes, W Shaw, E Chapman and C Driver. 2002. "Atmospheric Dust Dispersion Modeling System Utilizing a Geographic Information System." Poster presented at the *Annual SERDP/ESTCP Partners in Environmental Technology Technical Symposium and Workshop*, December 3-5, 2002, Washington, DC.

Allwine KJ, F Rutz, S Tzemos, C Driver, and R Kirkham. 2001. "Dust Dispersion Software System." Poster presented at the *Annual SERDP/ESTCP Partners in Environmental Technology Technical Symposium and Workshop*, November 27-29, 2001, Washington, DC.

A.5 Book Chapters

Scally R, FC Rutz, and KJ Allwine. 2005. "DUSTRAN: Predicting Dust Dispersion from Military Training Exercises." In: *GIS for Environmental Management*. ESRI Press. Available at <http://gis.esri.com/esripress/>. Accessed 05-06-2007.

A.6 Related Publications

Allwine KJ, JR, FC Rutz, JG Droppo, JR, JP Rishel, EG Chapman, SL Bird, and HW Thistle. 2006. *SPRAYTRAN 1.0 User's Guide: A GIS-Based Atmospheric Spray Droplet Dispersion Modeling System*. PNNL-16075, Pacific Northwest National Laboratory, Richland, WA.

Chapman EG, JP Rishel, FC Rutz, TE Seiple, RK Newsom, and KJ Allwine. 2006. *Dust Plume Modeling at Fort Bliss: Full Training Scenario*. PNNL-15935, Pacific Northwest National Laboratory, Richland, WA.

Chapman EG, JP Rishel, FC Rutz, TE Seiple, RK Newsom, and KJ Allwine. 2006. *Dust Plume Modeling at Fort Bliss: Move-Out Operations, Combat Training and Wind Erosion*. PNNL-16123, Pacific Northwest National Laboratory, Richland, WA.

Chapman EG, JP Rishel, TE Seiple, RK Newsom, FC Rutz, and KJ Allwine. 2006. *Interim Report: Dust Plume Modeling from Ranges and Maneuver Areas for Fort Bliss*. PNNL-15841, Pacific Northwest National Laboratory, Richland, WA.

Allwine KJ, FC Rutz, JG Droppo, S Bird, and HW Thistle. 2005. *SPRAYTRAN User's Guide: A GIS-Based Atmospheric Spray Droplet Dispersion Modeling System*. EPA/600/R-05/109, Washington, DC.

Berg LK, KJ Allwine, JR, and FC Rutz. 2004. "Incorporating a Full-Physics Meteorological Model into an Applied Atmospheric Dispersion Modeling System." In: *Proceedings of the 13th*

Conference on the Applications of Air Pollution. American Meteorological Society and Air & Waste Management Association), p. 5. American Meteorological Society, Boston, MA.

Allwine KJ, JR, FC Rutz, HW Thistle, and S Bird. 2004. "Demonstration of SPRAYTRAN—A GIS-Based Atmospheric Dispersion Model for Estimating Spray Drift." In: *Proceedings of the International Conference on Pesticide Application for Drift Management*, October 27-29, 2004, Waikoloa, Hawaii.